CS-N0W WPG8 Impacts on energy assets from extreme heat and heatwaves

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CS-N0W

Climate services for a net zero resilient world

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Key findings

This study presents the findings from an assessment of climate **(1) vulnerability** and **(2) exposure** of generic energy assets within the UK's energy system, and **(3) potential future impact** resulting from climate-driven extreme heat and heatwaves.

(1) Vulnerability: The assessment of vulnerability identified assets most to least vulnerable. Overall, the most vulnerable asset category was power sector networks. Several components were rated vulnerable (rating of 4), including distribution underground cables, Transmission and Distribution transformers, service lines and connections and switchgears, circuit breakers and other devices.

(2) Exposure: Assessment of UK exposure to extreme heat demonstrated that the UK's energy system is expected to be exposed to increased levels of extreme heat under future warming scenarios. The most extreme temperatures are concentrated throughout England and parts of Wales. Under Global Warming Level (2.5°C) (the highest GWL considered in this study) the south of England is projected to be exposed to temperatures of up to 42°C, with the rest of the UK (excluding coastal areas) projected to experience maximum temperatures of up to 36°C.

(3) Impact: Vulnerable assets may experience impacts from extreme heat under all warming scenarios. Under to the highest GWL (2.5°C) analysed here, low-medium impacts may be expected throughout the UK, with medium impacts concentrated across England (excluding the Southwest) and medium-high impacts projected in East Anglia. Historical analysis of extreme heat and the electricity system demonstrated that faults have often increased in frequency when surface temperatures exceed 30 °C. In the future, extreme heat may lead to indirect stress on the electricity system through increased demand for active cooling, but it is expected that the UK will likely add sufficient generation capacity to meet summer peaks in demand for cooling. However, the increased loading on electricity networks caused by active cooling may coincide with the periods of direct impacts of heatwaves and extreme heat on the energy system. Increased loading from cooling demand may be localised throughout the UK, which should be considered in system wide analysis.

These factors may compound to increase the likelihood of electricity shortfalls and loadshedding.

About CS-N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation, and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing, and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

Acronym	Definition
Al	Aluminium
BESS	Battery Energy Storage System
CCC	The Climate Change Committee
CCGT	combined cycle gas turbine
CCS	Carbon Capture and Storage
CEDA	Centre for Environmental Data Analysis
CSP	concentrating solar power
CS-N0W	Climate Services for a Net Zero Resilient World
Cu	Copper
DESNZ	Department for Energy Security and Net Zero
DNO	Distribution Network Operator
DTAS	Distribution and Transmission Automation Systems
ENWL	Electricity North West Ltd
GB	Great Britain
GDN	Gas distribution network
GWL	Global Warming Level
HVAC	Heating, Ventilation and Air Conditioning
HV	High Voltage
HVDC	High Voltage Direct Current
IPCC	Intergovernmental Panel on Climate Change
kV	kilovolts
LiBs	Lithium-ion Batteries
Li-ion	Lithium-ion

Acronym	Definition
LV	Low Voltage
MAE	Mean absolute error
MO	Met Office
MSE	Mean squared error
NaFIRS	National Fault and Interruption Scheme
NPG	Northern Powergrid
Ofgem	Office of Gas and Electricity Markets
PV	Photo Voltaic
PVC	Poly Vinyl chloride
REA	Rapid Evidence Assessment
RIIO-ED2	Revenue = Innovation + Incentives + Outputs' and 'ED' stands for Electricity Distribution 2
UKERC	UK Energy Research Centre
VRA	Vulnerability and Risk Assessment
XLPE	Cross-linked Polyethylene

Climate services for a net-zero resilient world

1. Executive summary

This report presents the findings from a study exploring the impact of extreme heat and heatwaves on energy assets within the UK energy system. The purpose of this work is to enhance DESNZ's and other decision-makers' understanding of climate risk to energy assets. The study consisted of six assessments, listed below:

- **Vulnerability assessment** identifying the relationship between energy assets and extreme heat (see Section 3.1 for key findings and for full methodology and results).
- **Exposure assessment** understanding the potential future occurrence of extreme heat across the UK (see Section 3.2 for key findings and Appendix 2 for full methodology and results).
- **Impact assessment** projecting potential levels of impact on vulnerable assets across the UK (see Section 3.3 for key findings and Appendix 3 for full methodology and results).
- **Prediction of temperature-related electricity faults** through analysis of historical electricity fault data and its causes (see Section 3.4 for key findings and Appendix 4 for full methodology and results).
- **Exploration of future energy scenarios** through review of existing literature discussing potential future energy scenarios and the indirect sensitivity of the energy system to extreme heat (see Section for key findings and Appendix 5 for full methodology and results).
- **Identification of potential adaptation options** from the literature to provide a high-level understanding of options to reduce vulnerability and exposure and increase resilience within energy assets (see Section 3.6 for key findings and Appendix 6 for full methodology and results).

Vulnerability of energy assets

Overall, the most vulnerable category of assets was found to be power networks. Several components were rated vulnerable (rating of 4), including distribution underground cables, transmission & distribution transformers, service lines and connections and switchgears, circuit breakers and other devices. The full list of assets ranked from most to least vulnerable are shown in Table 1. Increasing the resilience of these vulnerable assets should be a priority for adaptation efforts. Specific vulnerabilities for each asset have been identified in Section 3.1.

Table 1 Assets identified as most to least vulnerable, based on qualitative rating

Level of vulnerability	Asset	Asset category
Highly vulnerable (rating of 5)	No assets were identified as 'highly vulnerable'.	
Vulnerable (rating of 4)	Distribution underground cables	Power networks
	Transmission & distribution transformers	Power networks
	Service lines and connections	Power networks
	Switchgears, circuit breakers and other protection devices	Power networks
Potentially vulnerable (rating of 3)	Gas power plants and carbon, capture and storage	Electricity generation
	Nuclear power plants	Electricity generation
	Solar panels	Electricity generation
	Hydropower	Electricity generation
	Overhead lines: transmission, distribution and High Voltage Direct Current lines	Power networks

Level of vulnerability	Asset	Asset category
	Power electronics, converters, filters and interfaces	Power networks
	Control, monitoring and metering equipment	Power networks
	Distribution & transmission automation systems	Power networks
	Substation and network earthing systems	Power networks
	Battery storage systems	Energy storage
	Pumped hydro storage	Energy storage
	Compressed air energy storage	Energy storage
	Thermal energy storage	Energy storage
	Gas storage units	Energy storage
	Hydrogen storage units	Energy storage
	EV lithium-ion batteries	Energy storage
	Compressor valves and regulators	Natural gas infrastructure
	Gas importation terminals	Natural gas infrastructure
	Hydrogen electrolysers[1]	Hydrogen
	Hydrogen pipelines	Hydrogen
Resilient (rating of 2)	Wind turbines	Electricity generation
	Gas transmission and distribution networks	Electricity generation
	Hydrogen electrolysers[1]	Hydrogen

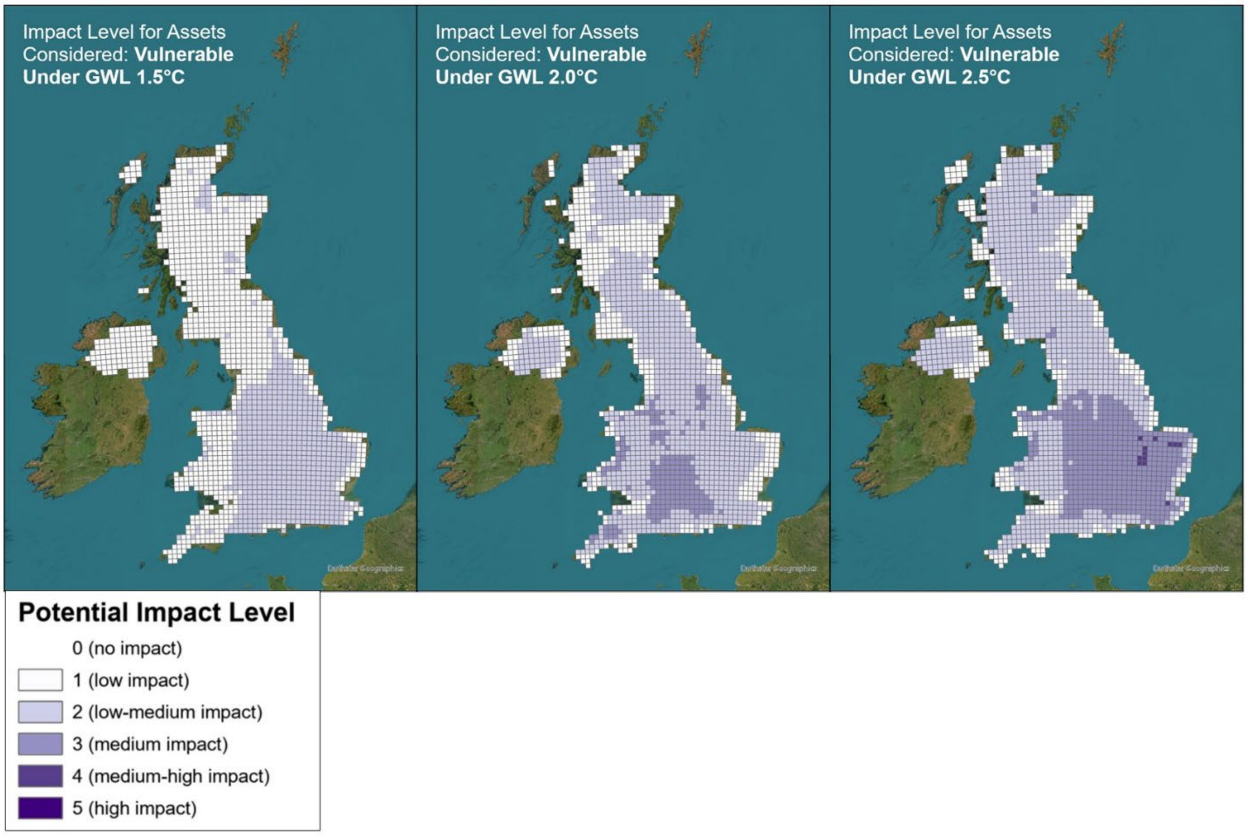
[1] Hydrogen electrolysers are 'potentially vulnerable' to heatwaves and 'resilient' to extreme heat.

Level of vulnerability	Asset	Asset category
Highly resilient (rating of 1)	No assets were identified as 'highly resilient'.	

Potential impact to energy assets

Assets rated as vulnerable may experience impacts from extreme heat under all warming scenarios (see **Error! Not a valid bookmark self-reference.**). According to the highest warming scenario analysed in this study, Global Warming Level (GWL) 2.5°C, low-medium impacts may be expected throughout the UK, with medium impacts concentrated across England (excluding the Southwest) and medium-high impacts occurring in East Anglia (see Section A.2.1.1 for uncertainties associated with climate data underpinning this analysis). This spatial distribution is associated with projected extreme temperature trends throughout the UK, where heating is concentrated in the South and East of England. Hence, more significant impacts are estimated in these regions. The nature of this impact will differ depending on the design of the energy asset and whether adaptive measures (cooling, insulation, etc.) are taken.

Figure 1 Potential impact level for energy assets considered vulnerable (vulnerability rating 4)



These findings were partially corroborated through a quantitative analysis of real-world data from the UK that identified a statistical relationship between the exposure of the UK electricity system to extreme heat and fault rates, using distribution network fault data between 2018 and 2022. Faults have historically increased in frequency above 30°C. There was insufficient historical data to accurately quantify this relationship at higher temperatures.

The asset-level impacts identified in this study may or may not translate to system-wide impacts. The added resilience from diversity and redundancy in the system was not factored into the analysis. The cascade of impacts from one asset to another, or from one asset into system-wide impacts, were not accounted for in the assessment. Compounding impacts, such as the impact from multiple assets experiencing increased faults or reduced efficiency and output were also not considered in the spatial analysis. This includes the heatwave in summer 2022 where temperatures reached 40°C. Furthermore, it is important to note that other climate-related hazards are experiencing increases in severity under climate change, which may lead to compounding impacts resulting from multiple hazards occurring at once; any assessment of asset site-selection should take into account all relevant climate-related hazards, where possible.

Future energy demand

In the future, extreme heat may lead to indirect stress on the electricity system through increased demand for active cooling, but it is expected that the UK will likely add sufficient generation capacity to meet summer peaks in demand for cooling. However, the increased loading on electricity networks caused by active cooling may coincide with the periods of direct heat impact on the energy system. Increased loading from cooling demand may be localised throughout the UK, which should be considered in system wide analysis. These factors may compound to increase the likelihood of electricity shortfalls and loadshedding.

2. Introduction

The UK has set clear targets for transitioning to a net zero economy: 81% reduction in emissions by 2035 and net zero by 2050. A core element of this transition is a shift to a low carbon energy sector. To ensure that the energy system transition is successful, and the benefits of investment are sustained, it is critical to understand the potential impacts from future climate change on the energy system. This study was commissioned to generate an initial evidence base on the relationship between energy assets within the energy system and climate-related hazards, specifically, extreme heat and heatwaves. The purpose of this work is to enhance DESNZ's and other decision-makers' understanding of **vulnerability and exposure of energy assets to extreme heat and heatwaves, and potential resultant impact**. The findings can support the identification and prioritisation of adaptation measures needed to ensure the resilience of existing energy assets and the design of the future net zero energy system.

This report is structured as follows. The Introduction presents the results of these assessments. The next part of the Introduction (**Section 2.1**), sets out the scope of the analysis, defining the specific energy sector assets in focus, the definition of the hazard, and the geographical coverage of the study. **Section 2.2** describes the methodological approach, which comprised seven different assessments that collectively inform the findings regarding vulnerability and future exposure of energy sector assets to extreme heat, likely future impacts and potential adaptation options. Key findings from each assessment are presented in **Section 3**. Conclusions, including key takeaways, evidence gaps, and potential further analysis are presented in **Section 4**. The detailed methodology and findings for each of the different assessments are provided in the Appendices.

2.1 Scope

The scope of the study was defined at inception. There are three key levels at which the scope has been set:

1. Assets in focus
2. Definition of extreme heat and heatwaves
3. Geographical coverage

The following sections present each defined scope.

2.1.1 Assets in focus

This study focuses on generic energy assets found within the UK energy system, grouped by ‘categories or components of the energy system. No single, comprehensive database of existing energy assets (their type, location and connectivity) across the UK was available for this analysis; therefore, this study does not present results in context of specific assets, but rather the vulnerabilities, exposure, and potential level of impact to generic energy sector asset categories and components. The development of central or comprehensive database would enable more granular, asset specific analysis, and would allow for an understanding of cross-system vulnerabilities and potential cascading impacts. The assets in focus are presented in Table 2.

Table 2 Energy asset categories and common assets considered in this study

Energy asset category	Key components
Electricity generation	• Gas power plants and CCS • Nuclear power plants • Solar panels • Wind turbines • Hydropower
Power networks components	• Overhead Lines (transmission, distribution, and HVDC lines) • Distribution underground cables • Transmission & distribution transformers • Service Lines and connections. • Switchgears, circuit breakers and other protection devices • Power electronics • Converters • Filters and interfaces • Control, monitoring and metering equipment. • Distribution & Transmission Automation Systems • Substation and network earthing systems
Energy storage	• Battery Storage Systems • Pumped Hydro Storage • Compressed Air Energy Storage • Thermal Energy Storage

Energy asset category	Key components
	• Gas Storage Units • Hydrogen Storage Units • Electric Vehicle (EV) lithium-ion batteries
Natural gas infrastructure	• Gas Transmission and distribution network • Compressor Valves and Regulators • Gas Importation Terminals
Hydrogen	• Hydrogen Electrolysers • Hydrogen Pipelines

Given that the scale of analysis was the specific energy sector assets and components, this study may miss out on some of the key characteristics of the UK energy system that affect the system as a whole. High levels of diversity (e.g. different types of power generation) and redundancy of function (e.g. high levels of generation capacity) may help to increase the resilience of the energy system, even if individual components are vulnerable. Additionally, the study may not capture cascading impacts, where an impact to one component of the system has knock-on effects to other components; or compound impacts, where simultaneous impacts to two different components or parts exacerbate the impact at the system-wide level. These types of system-wide characteristics were not considered due to a lack of available data showing asset type, location, redundancy, and connectivity, all of which are key factors in understanding whole-system vulnerability and resilience. This information would allow for analysis of interdependencies within the system and identification of single-points-of-failure which may exacerbate vulnerability.

This study intends to create an evidence base of information that could support the design of a resilient net zero energy system. Given the transformations required to achieve net zero, the future energy system will look significantly different to the current one. Analysis is first required to understand resilience of assets before exploring how their relative resilience contributes to system-wide resilience.

2.1.2 Definition of extreme heat and heatwaves

This study was commissioned to understand the relationship between energy assets and two climate-related hazards: extreme heat and heatwaves. Definitions of these hazards, derived from Met Office (MO) guidance, are provided below:

- **Extreme heat**: abnormally high air temperatures where temperatures exceed 27°C at a given location.
- **Heatwaves:** when a location records a period of at least three consecutive days with daily maximum temperatures meeting or exceeding the extreme heat temperature threshold. This temperature threshold differs across the UK.

UKCP18 (UK Climate projections) of maximum air temperature were analysed spatially to determine the potential level of exposure of, and impact on, all assets to extreme heat across the UK. The duration or frequency of exposure was not considered, meaning the spatial analysis of exposure and impact regards extreme heat, alone, and not heatwaves. The climate projections data was split into different bands, above the threshold of 27°C, to represent different levels of exposure to extreme heat. To analyse extreme heat in the context of physical infrastructure, an asset was defined as 'exposed' to extreme heat when the maximum temperature in its location was projected to exceed 27°C. This threshold is based on the MO definition of extreme heat. It was not based on the level at which faults increase in frequency as the analysis of fault data was completed following the analysis of exposure. This was largely due to the time it took to gain access to the NaFIRS datafiles (national fault inventory), and the NaFIRS dataset is limited in its completeness and quality, hence was not strong enough to warrant changing thresholds for extreme heat across the rest of the analysis. More details on the evidence gaps and suggested further research regarding the NaFIRS data can be found in Sections 4.2 and 4.3, respectively. The same threshold was used across the UK and across the different energy assets in this study for the purpose of consistency

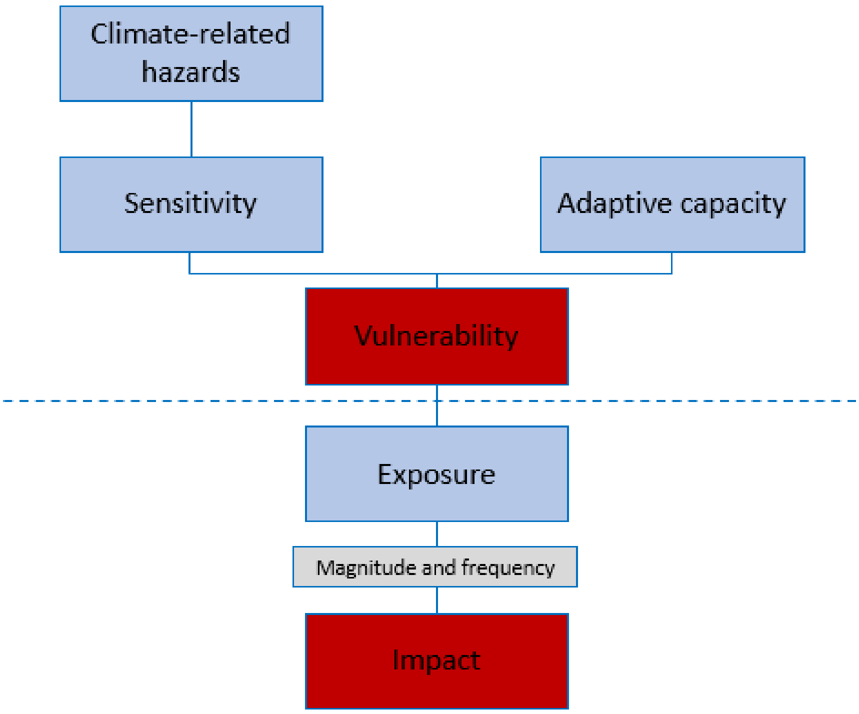
2.1.3 Geographic coverage

The geographic boundary of this study is UK wide. Spatial mapping is used to illustrate projections of extreme heat across the UK and implications for potential impacts. However, given the lack of data regarding location of energy assets, the study does not analyse the specific vulnerability, exposure, or impact of 'real' place specific assets. It is important to note that, while the UK's energy system is connected with other nations and geographies, this study does not consider indirect vulnerabilities associated with supply chains.

2.2 Approach

The vulnerability of an energy sector asset is determined by its sensitivity to a hazard (in this case, extreme heat) and its adaptive capacity, (its ability to adjust or respond to prevent or reduce potential damages). The impact of extreme heat on an energy asset is determined both by its vulnerability and by its exposure, in terms of magnitude and frequency. **Error! Reference source not found.** illustrates the relationships between climate-related hazards, sensitivity, adaptive capacity, exposure and impact. These key concepts form the overarching framework used to define the methodology for this study. Further description of these concepts can be found in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6: WGII Glossary), and common definitions of the terms are provided in Appendix 1.

Figure 2 Interactions of key terms defining climate impact



Based on the above framework, seven different assessments were used to collectively inform the findings regarding vulnerability and future exposure of energy sector assets to extreme heat, likely future impacts and potential adaption options. These are listed below:

1. **Vulnerability assessment:** The vulnerability of an energy sector asset is determined by its sensitivity to a hazard and its adaptive capacity. Sensitivity and adaptive capacity of each asset and energy system component was assessed through a Rapid Evidence Assessment (REA), stakeholder consultation, and expert review. Qualitative rating of asset vulnerability was applied to compare level of vulnerability between assets. Vulnerability to extreme heat and heatwaves was assessed against the defined threshold of 27°C for extreme heat (Section 2.1.2). Table 21contextualises the use of these thresholds, showing the approach taken for testing projected versus expected impacts at different levels of vulnerability and exposure. See for details of methodology and results.
2. **Exposure assessment:** Given the lack of available data regarding the location of energy assets, this study was not able to determine the exposure of specific energy assets across the UK. Instead, spatial maps of extreme heat projections across the UK under different Global Warming Levels (GWLs) were developed to answer the question: "If an asset was located in a specific region or location, how exposed would the asset be to extreme heat?". From this analysis, it is evident that extreme temperatures are already being experienced that surpass those projected in the lower GWL analysed here (GWL 1.5°C), therefore providing empirical data to validate the findings of this study. See Appendix 2 for details of methodology and results. To supplement this information, the REA collected qualitative information regarding the exposure of UK assets which is presented in Section 3.2.2.
3. **Impact assessment:** Building on the exposure assessment, the impact assessment sought to answer the question: "*if* an energy asset was located in a specific area, what level of impact may it experience?". Qualitative ratings of vulnerability were combined with quantitative ratings of exposure to derive an impact score. These scores were used to generate a series of maps showing potential levels of impact

from extreme heat to assets identified as highly vulnerable to highly resilient, under GWL 1.5°C, 2°C, and 2.5°C. See Appendix 3 for details of methodology and results.

4. **Predicting temperature-related energy faults:** The relationship between temperature and energy system faults was explored by using machine learning to analyse historical energy fault datasets (NaFIRS) and historical UK temperature datasets and 'predict' faults based on temperature fluctuations. See Appendix 4 for details of methodology and results.
5. **Extreme heat and the UK's future energy scenarios:** A literature review was conducted to consider the indirect impact of extreme heat in context of the UK's potential future energy demand. See Appendix 5 for details of methodology and results.
6. **Asset-specific adaptation options:** A REA was conducted to compile a list of potential adaptation options that could be implemented to address extreme heat within the energy system. These options were critically reviewed to determine their contribution to adaptation through a) reduction of vulnerability and b) reduction of exposure. See Appendix 6 for details of methodology and results.

3. Key findings

The key findings and high-level outcomes from each assessment are presented below. Full details of the methodology, results, and uncertainties are included in the appendix. Table provides navigation to each assessment and the corresponding appendix.

Table 3 Report structure of key findings and detailed findings/methodology

Assessment	Key findings	Detailed findings and methodology
Vulnerability assessment	**Section 3.1**	**Appendix 1**
Exposure assessment	**Section 3.2**	**Appendix 2**
Direct impact assessment	**Section 3.3**	**Appendix 3**

Predicting temperature-related faults	**Section 3.4**	**Appendix 4**
Extreme heat and the UK's future energy demand	**Section**	**Appendix 5**
Identification of asset-specific adaptation options	**Section 3.6**	**Appendix 6**

3.1 Vulnerability assessment

The following presents the key findings from the vulnerability assessment. This consists of a summary of the assessment of **sensitivity** and **adaptive capacity** (described in full in A.1.1 and outlined in Table). The summary of qualitative vulnerability ratings assigned to each asset are highlighted in Table 5. Qualitative ratings were assigned on a five-point scale where **1 = highly resilient** and **5 = highly vulnerable** (see Table 4). This is followed by a qualitative summary of the characteristics of asset vulnerability, per asset category.

Table 4 Definitions of ratings of vulnerability

Vulnerability rating	Definition of ratings
1	Highly resilient
2	Resilient
3	Potentially vulnerable
4	Vulnerable
5	Highly vulnerable

Table 5 Qualitative ratings of asset vulnerability to extreme heat and heatwaves

Asset categories	Asset	Hazard	Vulnerability rating (1-5)
Electricity generation	Gas Power Plants and CCS	Extreme heat	3
		Heatwaves	3
	Nuclear Power Plants	Extreme heat	3
		Heatwaves	3

Asset categories	Asset	Hazard	Vulnerability rating (1-5)
	Solar Panels	Extreme heat	3
		Heatwaves	3
	Wind Turbines	Extreme heat	2
		Heatwaves	2
	Hydropower	Extreme heat	3
		Heatwaves	3
Power networks	Overhead Lines - Transmission, Distribution, and HVDC lines	Extreme heat	3
		Heatwaves	3
	Distribution Underground cables	Extreme heat	4[2]
		Heatwaves	4[2]
	Transmission & Distribution Transformers	Extreme heat	4[2]
		Heatwaves	4[2]
	Service Lines and Connections	Extreme heat	4
		Heatwaves	4
	Switchgears, circuit breakers and other protection devices	Extreme heat	4
		Heatwaves	4
	Power Electronics, Converters, Filters and Interfaces	Extreme heat	3
		Heatwaves	3
	Control, monitoring and Metering Equipment	Extreme heat	3
		Heatwaves	3
	Distribution & Transmission Automation Systems	Extreme heat	3
		Heatwaves	3

[2] In the report 'Review of the Climate Resilience of the Net Zero Innovation Portfolio' (R1) developed under the CS-N0W programme, a qualitative vulnerability assessment of net zero technology is presented. The study determined that 'Power Networks' are 'potentially vulnerable' (vulnerability rating of 3). Whereas the study presented in this report (R2) determined that these specific assets within power networks are 'vulnerable' (vulnerability rating of 4). R2 explored vulnerabilities at a more granular level, assessing the vulnerability of 9 specific energy assets within the power network, whereas R1 conducted a higher-level review, assessing the vulnerability of power networks as a single unit. The increased granularity in R2 resulted in a higher vulnerability rating due to the inclusion of 'underground cables' and 'transformers'. These assets are more likely to experience long-term thermal stress (caused by rising average ground temperatures and limited flexibility for adjustments) and increased air conditioning demand driven by higher ambient temperatures, respectively.

Asset categories	Asset	Hazard	Vulnerability rating (1-5)
	Substation and network earthing systems	Extreme heat	3
		Heatwaves	3
Energy storage	Battery Storage Systems	Extreme heat	3
		Heatwaves	3
	Pumped Hydro Storage	Extreme heat	3
		Heatwaves	3
	Compressed Air Energy Storage	Extreme heat	3
		Heatwaves	3
	Thermal Energy Storage	Extreme heat	3
		Heatwaves	3
	Gas Storage Units	Extreme heat	3
		Heatwaves	3
	Hydrogen Storage Units	Extreme heat	3
		Heatwaves	3
	EV lithium-ion batteries	Extreme heat	3
		Heatwaves	3
Natural gas infrastructure	Gas Transmission and distribution network	Extreme heat	2
		Heatwaves	2
	Compressor Valves and Regulators	Extreme heat	3
		Heatwaves	3
	Gas Importation Terminals	Extreme heat	3
		Heatwaves	3
Hydrogen	Hydrogen Electrolysers	Extreme heat	2
		Heatwaves	3
	Hydrogen Pipelines	Extreme heat	3
		Heatwaves	3

No assets were identified as 'highly vulnerable' (rating 5) or 'highly resilient' (rating 1).

3.1.1 Electricity Generation

3.1.1.1 Nuclear Power Plants

Nuclear power plants were identified as **‘potentially vulnerable’ (rating 3)** to extreme heat and heatwaves. Fluctuations in temperature can reduce the cooling efficiency of nuclear power plants as cooling water temperature rises. Frequent or repeated heatwaves over time may cause faster degradation of infrastructure. However, it is understood that operators possess the capacity for adaptation to these hazards. They prioritise water use and ecosystem protection during shortages while complying with environmental permit discharge limits and engaging with local communities to maintain operational security. They also possess the financial capacity for technical interventions to address the impacts of extreme heat and to offset revenue losses during disruptions. Although some interventions can be costly, such as altering the cooling system of an operational plant, nuclear power plants are well-prepared to adapt to heat-related challenges through a comprehensive approach that balances operational needs with environmental considerations.

3.1.1.2 Gas Power Plants and CCS

Gas power plants were identified as **‘potentially vulnerable’ (rating 3)** to extreme heat and heatwaves. Fluctuations in temperature can reduce the cooling efficiency of gas power plants as the temperature of water used in cooling systems rises. As a result, frequent or repeated heatwaves or extreme heat events over time may cause faster degradation of infrastructure. Operators understand plant behaviour at high temperatures and implement solutions, such as circulating cooling systems and utilising heat-resistant materials. While challenges remain regarding water scarcity and maintaining turbine efficiency, operators may allocate emergency funds and invest in advanced cooling technologies (such as inlet air cooling) to plan and prepare for risks associated with heat. Additionally, where possible plant owners make use of natural measures such as vegetation near operational sites to provide natural heat shielding, which provides additional protection from extreme heat.

3.1.1.1 Solar Panels

Solar power plants were identified as **‘potentially vulnerable’ (rating 3)** to extreme heat and heatwaves. Increase in temperature above standard operating levels can reduce the efficiency of solar power plants. For every degree rise above 25°C, plant efficiency decreases by 0.2–0.5%. As a result, repeated heatwaves or extreme heat events over time may cause faster degradation of supporting infrastructure (such as solar PV arrays, cables, and mechanical structures). Organisations use real-time monitoring to adjust operations and adapt maintenance schedules based on temperature forecasts. Solar panels are designed to meet international standards, allowing them to operate at cell temperatures up to 85°C and ambient temperatures of 50°C, ensuring resilience during high-temperature events; however, efficiency may still decline under extreme heat and heatwaves. Adaptation of solar PV systems is understood as having a lower cost-burden than other, more mechanically complex assets, particularly when delivered at scale. Furthermore, the surrounding ecosystem, including soil, trees, and forests, plays a vital role in regulating temperatures and mitigating heat impacts near solar PV plants.

3.1.1.1 Wind Turbines

Wind turbines were identified as **'resilient' (rating 2)** to extreme heat and heatwaves, because predicted increases in UK temperature are less likely to cause turbine shutdown. However, high ambient temperatures could impact the power production due to decrease in air density and could accelerate wear and tear of the components and increase in cooling demand. Offshore wind farms are less affected by localised heat events, but they may face indirect sensitivity such as operational challenges due to shifts in bird migration patterns driven by warming climates. These changes can increase the risk of bird collisions with turbines, necessitating advanced monitoring systems to mitigate impacts. Onshore components, such as inverters, face more maintenance demands during high-temperature periods, straining operational capacities and increasing costs. It is understood that organisations are addressing these challenges by employing heat-resistant materials, high-temperature lubricants, and advanced cooling systems in turbine construction. Examples include nickel-based superalloys and thermal barrier coatings, which help turbines withstand high temperatures, and also CuproBraze technology (copper-alloy heat exchanger), which improves heat exchange efficiency. Onshore facilities also utilise measures like planting vegetation, which supports turbine performance by cooling the surrounding environment and benefiting the local ecosystem. Both onshore and offshore wind farms use innovative solutions to maintain reliability during extreme heat, this includes smart control systems, design improvements, and proactive measures—such as regular monitoring, staff training, and stakeholder engagement— which are optimising operations. Existing emergency funds and enhanced environmental strategies may further support resilience against heat-related challenges.

3.1.1.2 Hydro-Power

Hydropower plants were identified as **'potentially vulnerable' (rating 3) to extreme heat** and **heatwaves**. Extreme temperatures affect evaporation rates, water levels, and river flow. Studies suggest that a rise in temperature, combined with a decrease in precipitation, could significantly reduce river runoff, severely impacting hydropower generation. This reduction in runoff may also trigger cascading effects, such as increased strain on water storage systems and further reductions in power generation capacity. Organisations are implementing flexible operational plans, training staff to tackle heat-related challenges, and installing real-time monitoring systems to ensure efficient operations under high temperatures. While turbines and generators can function in higher ambient temperatures, their performance may decline during prolonged heatwaves; however, they can still generate electricity at reduced levels by efficiently utilising remaining water volumes in reservoirs. Financial capacity to implement adaptation measures is supported through emergency funds which can support investment in heat-resistant technologies and specialised insurance. The surrounding ecosystem also offers benefits, as forests and vegetation near reservoirs provide shade, lowering water temperatures and enhancing turbine efficiency while stabilising river flows during dry periods.

3.1.2 Power Network Components

3.1.2.1 Overhead Lines - Transmission, Distribution, and HVDC lines

OHLs were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as extreme temperatures prevent efficient heat dissipation, causes expansion, and affects tensile strength, which challenges capacity and safety clearance limit. Prolonged period of elevated temperature could cause faster degradation, combined with increased demand can push the OHLs to their design limits (in UK conductor are currently designed for maximum operating temperature of 75°C, and the average assumption for ambient temperature during designing are set at 2°C for winter, 9°C for spring and autumn, and 20°C for summer) increasing the risk of outages. UK DNOs has a good understanding of the behaviours of OHLs and are addressing these challenges by incorporating higher temperatures into design policies and replacing existing with taller poles where needed, though financial capacity to implement adaptation measures might be slightly impacted because of Ofgem approving only 90-95% of the proposed investment in the last price control RIIO-ED2 (Revenue = Innovation + Incentives + Outputs' and 'ED' stands for Electricity Distribution 2) review period.

3.1.2.2 Distribution Underground Cables

Underground cables were identified as **'vulnerable' (rating 4)** to extreme heat and heatwaves. Extreme temperatures can prevent efficient heat dissipation and cause excessive stress due to frequent thermal cycling, affecting capacity and mechanical strength. Prolonged period of elevated temperature could degrade the cables faster. In the UK, paper-insulated lead-covered cables are rated/designed for a maximum temperature of 65°C, Poly Vinyl chloride (PVC) cables for 70°C, and Cross-linked Polyethylene (XLPE) cables for 95°C. The thermal ambient temperatures currently used for cable designing in UK are 15°C for summer, 12°C for spring and autumn, and 10°C for winter. Due to an increase in average ground temperature, underground cables may experience worse long-term thermal stress in comparison to OHL. Organisations' capacity to adapt is limited due to maintenance challenges and limited monitoring of underground cables operating temperature. Though organisations have started incorporating climate-driven temperature trends into investment plans, financial capacity might be limited due to system wide investment decisions; for example, in the most recent price control RIIO-ED2 review period, Ofgem approving 90-95% of requests, leaving 5-10% unapproved. Ecosystem capacity is limited, as the thermal mass of soil may help cables adapt to short-term heat but not to prolonged increases in extreme heat.

3.1.2.3 Transmission & Distribution Transformers

Transformers were identified as **'vulnerable' (rating 4)** to extreme heat and heatwaves, as extreme temperatures prevent efficient heat dissipation, accelerates insulation degradation, affecting capacity and shortening lifespan. Prolonged period of high temperature combined with increased demand for cooling can cause the design limits to be reached faster, further accelerating the degradation. UK transformers are designed for ambient temperatures up to 40°C, with derating[3] occurring above this threshold. Distribution transformers are more vulnerable than transmission transformers due to lack of forced cooling systems and being generally operated at higher loads in comparison to transmission transformers. Organisations understand the behaviour of transformers under high temperatures and are beginning to consider climate change in their investment plans, but technical adaptive capacity is impacted by the immediate surroundings (for example, located in a basement of a commercial building or close to heavily air conditioned building), and is limited particularly for transformers already operating at high loads, without forced cooling, and with limited monitoring (especially the case for older transformers). Financial capacity to implement adaptation measures might be affected by Ofgem's most recent price control review (RIIO-ED2 period), where 90-95% of proposed investment was approved (5-10% unapproved).

3.1.2.4 Service Lines and Connections

Service lines were identified as **'vulnerable' (rating 4)** to extreme heat and heatwaves, as elevated ambient temperatures impede heat dissipation, reducing current-carrying capacity. This can degrade insulation in underground lines, create hotspots, and, for overhead service lines, reduce tensile strength and cause excessive sag. Service lines are typically less robust and potentially more sensitive than underground cables, especially older lines. Utilities have a differing view based on their experience; some consider service lines more sensitive than underground cables and overhead lines, while some consider them less sensitive. Joints and connections are sensitive to extreme heat due to increased stress and loss of tensile strength, which can lead to mechanical failures and reduced efficiency in electrical transfers. Evidence indicates that both cables and joints are sensitive; however, there is some disagreement whether one is more sensitive than the other. Some evidence suggests that joints and connections are more sensitive (citing experiencing 33 kV joint

[3] To ensure the safe and efficient operation, energy assets are assigned 'rating capacities' which determine the power capacity at which that asset can or should be operated at. 'Derating' means that it has been recommended that an asset reduces its capacity due to external factors, in this case due to ambient temperatures exceeding asset design temperature thresholds. This helps to avoid degradation of insulation and critical components.

failures during hot summer conditions) and are likely to fail before cables. The current evidence is inconclusive.

Prolonged high temperatures accelerate degradation and push service lines to their technical limits. Similarly, prolonged high temperatures exacerbate stress on joints and connections, potentially pushing them to their technical and mechanical limits faster.

Organisations address these challenges by factoring in temperature extremes in investment plans, but their capacity is limited due to challenges in maintaining underground service lines. Due to being underground, they may handle higher temperatures, but technical capacity to adapt to prolonged exposure to higher temperatures is limited. Similarly, joints and connections can withstand short-term heat but suffer from cumulative stress over time. Financial capacity may be limited; Ofgem approved only 90-95% of proposed investment, potentially affecting financial capacity in the last price control review, the RIIO-ED2 period.

3.1.2.5 Switchgears, Circuit Breakers, and Other Protection Devices

Switchgears, circuit breakers, and other protection devices were identified as **'vulnerable' (rating 4)** to extreme heat and heatwaves, with temperatures above 40°C causing reduced capacity, degradation, and potential failures. Prolonged period of high temperature could also raise temperature in switch rooms above optimal levels, making them vulnerable to faults. Insufficient cooling and temperature fluctuations increase vulnerability compared to electricity generation assets. Organisations manage heat through natural ventilation, forced cooling, and air conditioning, while natural and passive cooling methods support heat management for outdoor and indoor assets. Ofgem approved only 90-95% of proposed investment in last RIIO-ED2 price control may affect the capacity of asset owners to secure the maximum investment required.

3.1.2.6 Power Electronics, Converters, Filters and Interfaces

Power electronics, converters, filters, and interfaces devices were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, with elevated temperatures reducing efficiency, causing power losses, and potentially damaging critical components like capacitors. Prolonged period of elevated temperature could lead to accelerated degradation and design limits to be reached faster. To address this, organisations enhance adaptive capacity through preventive maintenance, specialised training, advanced cooling systems, heat-resistant materials, and real-time monitoring. Financial planning, R&D investments, adherence to regulatory standards, and system-wide coordination between stakeholders and asset-owners further ensures reliable performance and resilience under high-temperature conditions.

3.1.2.7 Control, Monitoring and Metering Equipment

Control, monitoring, and metering equipment were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as semiconductors (which are the basic building block of these devices) perform optimally at lower and stable temperatures. Prolonged period of elevated temperature could lead to accelerated degradation of components. High temperatures can cause control systems to malfunction due to incorrect measurements and affect the performance of supporting communication infrastructure, further affecting reliability. Organisations address these challenges by carrying out regular calibration checks, preventive maintenance, and cooling system upgrades. Technical adaptive capacity, in general is ensured by installing assets in shaded and ventilated location but could be significantly impacted by the asset's immediate surroundings. Sustained or repeated extreme temperature events will accelerate the degradation, increasing the difficulty and cost of repair.

3.1.2.8 Distribution & Transmission Automation Systems (DTAS)

DTAS were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as high temperature can affect the reliability of control, monitoring, and metering equipment, which are the basic building block of these systems. High temperature can reduce the accuracy and reliability of sensors and control devices by causing recording of incorrect measurements and affect the performance of supporting communication infrastructure (such as wireless network that rely on batteries), further affecting reliability. Incorrect measurements can also increase the risk of data issues, exacerbates consequences of cybersecurity bridges and power system faults and safety due to unexpected operational states during maintenance. Organisations ensure resilience by using heat resistant material, installing in shaded locations, and arranging for cooling systems and ventilation where needed. Sustained or repeated extreme temperature events will accelerate the degradation, increasing the difficulty and cost of repair.

3.1.2.9 Substation and Network Earthing Systems

Earthing systems were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as it can affect the earth resistance and accelerate corrosion, which can affect the effectiveness of the earthing system. Extreme heat can put excessive strain on earthing grid joints due to thermal expansion as well as soil drying out. Increase in average ground temperature due to an extended period of high temperature can significantly impact the effectiveness of earthing systems. Organisations address these by regular maintenance, calibration checks, and developing emergency response plans. Some technical adaptive capacity exists, as earthing systems are designed for some seasonal and regional variation but may not have the capacity to adapt under prolonged exposure to extreme temperature. Upgrading large earthing systems (such as substation earthing grid) could be capital intensive, therefore financial capacity may be limited, unless extreme temperature impact on earthing systems has already been considered in investment plans.

3.1.3 Energy Storage

3.1.3.1 Battery Energy Storage Systems (BESS)

Li-ion BESS were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as ambient temperatures higher than 35°C (optimal temperature range is 15°C to 35°C) accelerate thermal aging and degrade all components within Li-ion batteries. High temperatures can affect BESS power, capacity and potentially causing irreversible damage to the batteries. Prolonged operation under high temperature can overwhelm BESS cooling systems posing safety risks such as thermal runaway and explosions. Similarly, cooler temperatures *below* the optimum temperature range affects battery performance due to poor ion movement, reducing battery capacity and efficiency. This can lead to decreases in energy output and slower charging rates, as cold temperatures increase internal resistance and slow electrochemical reactions. Developers and manufacturers have a strong understanding of risk to BESS from high temperature and mitigate risks through regular maintenance, design improvements, and passive cooling strategies. BESS developers believe that BESS has sufficient technical capacity to adapt to extreme heat, as BESS HVAC systems are designed to handle temperatures up to 45°C and should not be affected by minor increases in ambient temperature. But prolonged exposure to extreme heat can still challenge BESS system resilience.

3.1.3.2 Pumped Hydro-Storage

Pumped hydro storage systems were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as they depend on stable temperatures for optimal component efficiency and water retention. During heatwaves, these sensitivities are exacerbated, leading to increased reservoir evaporation and reduced water availability, thereby placing additional stress on mechanical components due to elevated operating temperatures. To enhance their adaptive capacity, organisations managing pumped hydro storage systems are implementing regular maintenance and thermal management practices to maintain the performance of pumps and generators during heatwaves. Advanced cooling technologies such as closed-loop cooling for turbines and generators, air-cooled heat exchangers, and oil-based cooling for transformers, are now employed to minimise heat-related impacts.

Reservoir thermal management strategies, including floating solar panels and reflective covers, help reduce evaporation and heat absorption.

Plant owners possess the financial capacity for equipment maintenance and infrastructure improvements through budgeting for emergency repairs to ensure reliable operations under extreme conditions. By maintaining and enhancing local ecosystems, organisations can buffer the effects of extreme heat, thereby supporting both infrastructure resilience and environmental sustainability.

3.1.3.3 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) systems were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as their efficiency in air compression, cooling, and turbine performance relies on lower temperatures. An increase in temperature raises energy consumption for compression, with each 1°C rise potentially increasing energy use by approximately 1-2% and reducing cooling efficiency by 0.5-1% per degree Celsius. Prolonged exposure to high temperatures can lead to increased wear and tear on mechanical components, degrading insulation materials and raising maintenance costs. Modern CAES plants employ intercoolers and aftercoolers to regulate compressed air temperatures. Organisations are allocating funds for regular maintenance and infrastructure improvements along with emergency repairs to ensure reliable operations. Additionally, organisations leverage predictive analytics to adjust operations and maintenance schedules in response to heatwaves, coordinating with meteorological services to optimise responses. The use of natural cooling systems, such as surrounding vegetation, further aids in mitigating heat stress on CAES units, enhancing their resilience against extreme temperatures.

3.1.3.4 Thermal Energy Storage

Thermal storage units were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as their operation relies on the temperature difference (ΔT) between ambient air and the storage system. In periods of prolonged high temperature, cooling systems will become less efficient, leading to potential drop in efficiency and damages to the asset. Hot storage units (400–1000°C) are less impacted due to their robust insulation (and a marginal decrease in the ΔT), but ancillary equipment like offloading pumps is vulnerable to extreme heat. Cooling storage units, in contrast, are particularly sensitive, as the ΔT has the potential to increase when exposed to extreme heatwaves, leading to efficiency losses (up to 30% when ΔT is doubled) and an increased risks of component failure. While insulation provides some technical resilience, its design is often capped for cost-effectiveness, and there is limited regulatory guidance for extreme heat adaptation. Organisations attempt to mitigate risks through emergency budgets, passive cooling measures, and adaptive expertise, but the resilience of thermal storage systems remains constrained by financial, technical, and ecosystem limitations, especially during prolonged heatwaves.

3.1.3.5 Gas Storage Units

Gas energy storage units were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as stable temperatures are crucial for maintaining gas pressure and tank integrity. High ambient temperatures cause gas expansion, which increases pressure and places additional strain on cooling systems. During heatwaves, this sensitivity is exacerbated, leading to a higher risk of long-term damage and reduced efficiency, making effective cooling and monitoring essential. To enhance their adaptive capacity, asset owners managing gas storage units have implemented upgraded monitoring systems and provided regular training for staff to address heat-related challenges. Financial strategies, including regular cost-benefit analyses and contingency funds, enable efficient management of resources needed for necessary adaptations. Additionally, where possible, organisations are utilising natural cooling systems, such as wetlands and green roofs, to reduce heat stress on storage units. These ecosystem-based strategies not only buffer the effects of extreme heat but also provide ongoing protection for both infrastructure and the environment. However, realising the benefits of ecosystem-based measures takes time to allow for growth. The effectiveness of these measures is determined by a number of factors, including the specific local environment, space available, and investment for maintenance. While beneficial, they work best alongside technological cooling and real-time monitoring.

3.1.3.6 Hydrogen Storage Units

Hydrogen storage units were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves given that storage capacity and production efficiency rely on temperature conditions of a particular range. Overground storage requires more cooling to maintain operations and would therefore be more sensitive to temperature increases. Organisations managing hydrogen storage units should have robust operational procedures and employ skilled personnel to effectively handle extreme heat. Existing natural ecosystems around storage sites can be integrated to provide additional cooling benefits, helping reduce the overall thermal load on storage units. Hydrogen asset owners are understood to possess the financial capacity to maintain and upgrade hydrogen storage infrastructure to withstand extreme heat.

3.1.3.7 EV Lithium-ion Batteries

EV lithium-ion batteries were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves, as high ambient temperature can cause them to operate beyond the optimal temperature range (15°C to 35°C) for Li-ion batteries, increasing internal resistance and accelerating degradation. This affects the battery's power, capacity, and eventually its range. At high temperatures, EVs charge slowly, increasing the charge time, which further impacts the performance. Prolonged operation at high temperature can overwhelm battery cooling systems, and insufficient cooling can lead to irreversible damage and thermal runaway. Similarly, cooler temperatures *below* the optimum temperature range affects battery performance due to poor ion movement, reducing battery capacity and efficiency. This can lead to decreases in energy output and slower charging rates, as cold temperatures increase internal resistance and slow electrochemical reactions. Manufacturers have a strong understanding of risk to EV batteries from high temperature and mitigate risks through design improvements. EV LiBs can handle intermittent exposure to extreme heat, but prolonged exposure and operation under extreme heat are expected to pose a significant challenge to their optimum and safe operation.

3.1.4 Natural Gas Infrastructure

3.1.4.1 Gas Transmission and Distribution (T&D) Network

Gas utility operators view gas transmission and distribution networks in the UK as '**resilient' (rating 2)** to extreme heat and heatwaves**,** as gas pipelines in the UK are currently designed for ambient temperatures between -30°C and 60°C and operate well below 30% of their specified minimum yield strength. Therefore, currently gas T&D companies do not give specific consideration to forecasted extreme temperatures in investment plans submitted to Ofgem. Extended period of high temperature can have some impact, primarily due to the impact on supporting IT equipment and instrumentation performance on due to overheating. There is an indirect risk to pipes, joints, and connections due to soil subsidence due to dryness of soil. Sufficient technical capacity for resilience exists as gas T&D networks are designed to international standards and are in operation within countries with much higher ambient temperatures than the UK. Indirect risks are addressed by conducting surveys to identify areas prone to subsidence and replacing less ductile iron gas mains pipes with less vulnerable polyethylene pipe.

3.1.4.2 Compressor Valves and Regulators

Compressor valves and regulators in natural gas infrastructure were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves because high temperatures can reduce the compressor's ability to transfer gas. Higher ambient temperature reduces the power output of the gas turbine that drives the compressor and accelerates wear and tear on the valves and regulator. Indirect sensitivity exists as a result of suboptimal performance of supporting IT equipment and instrumentation caused by insufficient cooling at high temperatures. Gas utilities believe that sufficient technical adaptation exists because gas network assets are designed to international standards and have operated in places with greater ambient temperatures than the UK. However, capacity to adapt under extended periods of high temperature can be impacted by impacts on supporting IT equipment and instrumentation.

3.1.4.3 Gas Importation Terminals

Gas importation terminals were identified as **'potentially vulnerable' (rating 3)** to extreme heat and heatwaves because the natural gas arrives in a liquid state (-160°C) and is converted to gas using vaporisers. Higher ambient temperature can slightly improve the vaporisation efficiency; however, it also leads to an increase in cooling demand, heat ingress and boil-off gas rate. This can lead to safety risks, reduced storage capacity, and pressure build-up. Prolonged periods of high temperature can stress equipment, cause thermal expansion, and affect the accuracy of flow meters. Organisations address these challenges by carrying out reviews of maintenance regimes and operational procedures to account for increasing temperatures. Some technical adaptive capacity exists as these assets are manufactured to international standards. They also partially benefit from natural cooling via wind and sea water evaporation.

3.1.5 Hydrogen

3.1.5.1 Hydrogen Electrolysers

Hydrogen electrolysers are considered as '**resilient' (rating 2) to heatwaves** as they operate in the range of 27-29°C and above, and cooling systems exist with controls and are robust for ~40°C. However, these devices are considered **'potentially vulnerable' (rating 3)** to heat waves as prolonged periods of high temperature adds stress on cooling parts and might lead to a fatigue/ failure of the device. The location of hydrogen can differ between developments, as some will select location according to the availability of water for the production and cooling; hence, cooling demand during times of extreme heat is manageable through access to water supply. Organisations already implement a robust safety culture through using electrolyser control systems as well as regular operation and maintenance regimes that ensure the system is in optimal condition to withstand heat variations. This process should continue and be regularly reviewed in-line with evolving policy and manufacturer recommendations.

3.1.5.2 Hydrogen Pipelines

The seals connecting hydrogen pipelines are **potentially vulnerable to extreme heat (rating 3),** but pipelines are less vulnerable as they are buried below ground. Pressure and temperature probes are installed along pipelines for continuous monitoring. Pipelines are constructed using robust materials and tested methods to handle heat fluctuations and are buried at depths that minimise surface temperature effects. Anticorrosive coatings and materials like PE80 and PE100 are commonly used, though hydrogen pipelines may require larger diameters or higher pressures due to energy density requirements. The UK gas network is well-equipped to manage emergencies, enabling rapid stopping and rerouting of gas flow while isolating affected sections. Asset owners of the gas network possess the financial capacity to identify and complete repairs, where necessary.

3.2 Exposure assessment

The assessment to exposure of UK energy assets to extreme heat was limited by a lack of available data regarding location of assets across the country. To understand the level of exposure, two steps were taken. First, spatial maps of extreme heat projections across the UK were developed to answer the question: “If an asset was located in a specific region or location, how exposed would the asset be to extreme heat?”. Second, the REA collected qualitative information regarding the exposure of UK assets to supplement the spatial analysis. The results from these exercises are presented separately below.

3.2.1 UK exposure to extreme heat

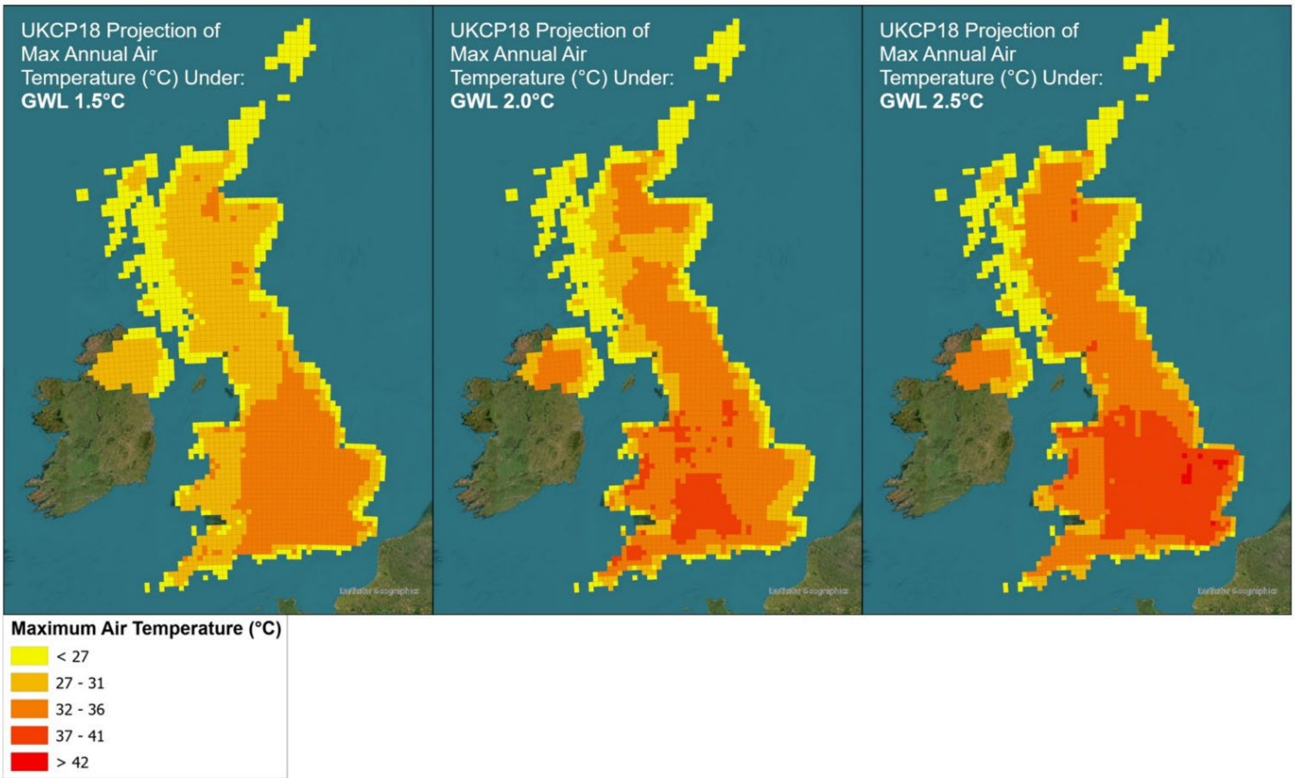
Projections of UKCP18 bias-corrected maximum air temperature data were mapped across the UK under different warming futures known as Global Warming Levels or GWLs. The GWLs used in this analysis are 1.5°C, 2°C and 2.5°C, representing future scenarios, in which global average air temperature reach the temperature defined by each GWL, projected to be reached by 2050. The 2023 UN GAP report states that Nationally Determined Contribution (NDCs) made under the Paris Agreement would put the world on track for limiting temperature rise to 2.9°C above pre-industrial levels this century, and fully implementing conditional NDCs would lower this to 2.5°C. Therefore, the decision was made by DESNZ to use a range between 1.5 °C, 2°C, and 2.5°C to show the outcome most aligned with current commitments. More information on GWLs, climate ensemble member selection and data inputs can be found in Section A.2.1.1.

For the purposes of our study, an asset is defined as 'exposed' when the maximum temperatures in its location are projected to exceed 27°C, defined as the threshold of 'extreme heat' (See Section). Exposure increases up scale from 1-5, with 5 indicating that temperatures will exceed 42°C. Only the *annual maximum* air temperature data was used to assess exposure to extreme heat.[4] The duration or frequency of exposure was not considered, meaning the spatial analysis of exposure and impact regards extreme heat, alone, and not heatwaves.

The results from the exercise are shown in Figure below. The general trend is clear. As, extreme heat is projected to occur more severely in the UK under higher GWLs. The south of England is projected to be exposed to the highest temperatures of up to 42°C. Most of the rest of the UK are projected to experience average annual maximum temperatures of up to 36°C under the highest GWL (2.5°C), excluding coastal areas which are projected to have lower extreme temperatures under all GWLs.

[4] While it can be assumed that these maximum temperatures are projected to occur in the summer months, the use of the annual maximum does not account for seasonal changes in extreme heat in this study. This data also does not account for the variance in heat parameters, such the difference between minimum and maximum air temperatures known as the diurnal temperature range, which can be a useful indicator of extreme heat.

Figure 3 UK-wide exposure to extreme heat under GWLs 1.5°C, 2°C and 2.5°C



These results should be used with a high degree of caution. There are substantial uncertainties associated with climate models in general, particularly those projected at a high resolution.[5] Climate models tend to be more accurate when projecting means, rather than extremes as done here, and bias correction has been applied to the data, potentially skewing some of the more severe extremes (more details on the uncertainties and the bias correction methodology can be seen in Appendix 2). The temperatures presented are the highest temperatures projected over the 20-year period spanning the year the relevant GWL

[5] There is significant uncertainty associated with the use of climate projections data that underpins these maps. First, there is significant uncertainty surrounding the future global warming level the world will reach, which is dependent on the success of global mitigation efforts as well as complex feedback loops and tipping points that are difficult to model. There is significant disagreement between different ensemble members, as each member makes different assumptions that result in varying outputs that project different potential futures with regards to the magnitude of extreme heat events. There is also significant uncertainty associated with high resolution projections. The data presented here on a 12km² grid is relatively high resolution, which risks indicating a false sense of certainty within the findings for each 12km² area. Given the uncertainty associated with these projections, the findings should be considered indicative only. More detailed information on the uncertainty associated with this methodology can be found in Section A.1.1.2.

was met. Hence, these maximum temperatures are inherently low frequency extreme events, the frequency and magnitude of which climate models struggle to accurate project.

Already, temperatures experienced in the previous few years indicate that these projections may be inaccurate. During a heatwave in July 2022, temperatures across much of England reached the high thirties, exceeding the most extreme temperatures projected in a 1.5 °C GWL scenario. The highest temperature reached was 40.3 °C, a new record for the UK [1].

The empirical data from the 2022 heatwave indicates that we are trending towards the higher end of the extreme temperatures projected by the ensemble. Therefore, in this section and Section 3.3 on Impacts, we have chosen to present the maximum modelled outcomes in UKCP18 data under the GWLs of 1.5°C, 2°C, and 2.5°C (see Section A.2.1.1 for further details of the input data). The minimum and median outcomes are also considered in Sections A.2.2 and A.3.2.

3.2.2 Exposure of energy assets across the UK

In the absence of a comprehensive registry of energy asset locations across the country, an REA was conducted to collect qualitative information on approximate location of asset types throughout the UK and what this might mean in terms of exposure to extreme heat. Table 6 summarises the key REA findings on exposure. The vulnerability ratings are provided in the right-hand column for context. This qualitative information can be interpreted alongside the temperature maps shown in the previous section.

Table 6 Key REA findings on exposure

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
Electricity generation	Gas Power Plants and CCS	Gas power plants may be exposed to extreme heat and heatwaves as they are distributed across the UK, with a slightly higher concentration in the southern and eastern regions that are typically warmer.	Extreme heat	3
			Heatwaves	3
	Nuclear Power Plants	Nuclear power plants are expected to be highly exposed to extreme heat which can reduce cooling water availability and increase its temperature.	Extreme heat	3
			Heatwaves	3
	Solar Panels	Solar PV systems may be exposed to heat events in the UK because they are installed above ground or on roofs and designed to absorb sunlight.	Extreme heat	3
			Heatwaves	3
	Wind Turbines	Wind turbines are expected to be highly exposed to extreme heat as they are installed above ground or sea, so have direct exposure to air and sunlight.	Extreme heat	2
			Heatwaves	2
	Hydro	Hydropower plants may have high exposure to extreme heat, as reservoirs and river flows are directly exposed to sunlight.	Extreme heat	3
			Heatwaves	3
Power networks	Overhead Lines - Transmission, Distribution,	Overhead lines may be highly exposed to extreme heat due to their above-ground installation and direct sunlight exposure. Lines in urban areas experience higher temperatures due to the heat island effect.	Extreme heat	3
			Heatwaves	3

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
	and HVDC lines			
	Distribution Underground cables	Underground cables may have lower exposure to ambient extreme heat due to reduced direct sunlight exposure. [Ricardo inhouse experts] However, they are more exposed to long-term thermal stress, as rising average ground temperatures and factors like soil moisture can limit heat dissipation.	Extreme heat	4[6]
			Heatwaves	4[6]
	Transmission & Distribution Transformers	Transformers located outdoors may have higher exposure to extreme heat. Outdoor transformers may have higher exposure to extreme heat due to direct sunlight. Indoor transformers could experience lower temperatures if adequately ventilated. Transmission transformers may benefit from natural cooling despite being exposed to environmental variations. Indoor transformers in confined spaces like substations or car parks may face heat exposure similar to outdoor transformers due to surrounding concrete.	Extreme heat	4[6]
			Heatwaves	4[6]
	Service Lines and Connections	Overhead service lines, joints, and connections may have high exposure to extreme heat, with urban areas experiencing heat island effects. Underground service lines are expected to have lower exposure but may still face risks from rising temperature. Cable terminations transitioning from underground to overhead	Extreme heat	4
			Heatwaves	4

[6] In the report 'Review of the Climate Resilience of the Net Zero Innovation Portfolio' (R1) developed under the CS-N0W programme, a qualitative vulnerability assessment of net zero technology is presented. The study determined that 'Power Networks' are 'potentially vulnerable' (vulnerability rating of 3). Whereas the study presented in this report (R2) determined that these specific assets within power networks are 'vulnerable' (vulnerability rating of 4). R2 explored vulnerabilities at a more granular level, assessing the vulnerability of 9 specific energy assets within the power network, whereas R1 conducted a higher-level review, assessing the vulnerability of power networks as a single unit. The increased granularity in R2 resulted in a higher vulnerability rating due to the inclusion of 'underground cables' and 'transformers. These assets are more likely to experience long-term thermal stress (caused by rising average ground temperatures and limited flexibility for adjustments) and increased air conditioning demand driven by higher ambient temperatures, respectively.

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
		may be particularly sensitive areas exposed to direct sunlight and heat.		
	Switchgears, circuit breakers and other protection devices	Exposure of switchgears and related devices to extreme heat may vary by location. Outdoor units are directly exposed to sunlight, while indoor units may experience slightly lower temperatures with proper ventilation.	Extreme heat	4
			Heatwaves	4
	Power Electronics, Converters, Filters and Interfaces	Power Electronics, Converters, Filters, and Interfaces are exposed to varying temperatures based on their location. Outdoor units may be directly exposed to sunlight and high temperatures, whereas indoor units experience slightly lower temperatures, assuming adequate ventilation is in place.	Extreme heat	3
			Heatwaves	3
	Control, monitoring and Metering Equipment	Control, monitoring, and metering equipment may be exposed to different temperatures depending on their location. Outdoor equipment faces direct sunlight and high temperatures, while indoor equipment experiences somewhat lower temperatures, assuming adequate ventilation is provided.	Extreme heat	3
			Heatwaves	3
	Distribution & Transmission Automation Systems	Distribution & Transmission Automation Systems may be exposed to extreme heat through thermal stress on components and reduced efficiency of cooling systems.	Extreme heat	3
			Heatwaves	3
	Substation and network	Substation and network earthing systems may be exposed to extreme heat primarily through indirect m as they are situated below ground and are not directly exposed to sunlight.	Extreme heat	3
			Heatwaves	3

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
	earthing systems			
Energy storage	Battery Storage Systems	Battery storage systems are expected to have high exposure to heatwaves and extreme heat, as most large-scale systems are located outdoors.	Extreme heat	3
			Heatwaves	3
	Pumped Hydro Storage	Pumped hydro storage components may have relatively low exposure to heatwaves, as they are often in cooler, high-altitude regions.	Extreme heat	3
			Heatwaves	3
	Compressed Air Energy Storage	Compressed air energy storage units are expected to have low exposure to heatwaves, as compressed air is stored underground, reducing ambient temperature effects.	Extreme heat	3
			Heatwaves	3
	Thermal Energy Storage	Thermal energy storage units may have high exposure to heatwaves, as many are outdoors. Ancillary equipment in enclosed metal spaces may face higher temperatures.	Extreme heat	3
			Heatwaves	3
	Gas Storage Units	Gas storage units may be exposed to heatwaves and extreme heat as they are often located outdoors and subjected to high ambient temperatures.	Extreme heat	3
			Heatwaves	3
	Hydrogen Storage Units	Hydrogen storage units may be exposed to heatwaves due to their outdoor placement, where ambient temperatures can vary.	Extreme heat	3
			Heatwaves	3
			Extreme heat	3

Climate services for a net-zero resilient world

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
	EV lithium-ion batteries	EV lithium-ion batteries may be indirectly exposed to heatwaves. When vehicles are parked in open spaces, battery temperatures may rise compared to shaded areas.	Heatwaves	3
Natural gas infrastructure	Gas Transmission and distribution network	Underwater pipelines corrode faster at high temperatures. However, since most of the gas network is underwater or underground, it is not directly exposed to extreme heat.	Extreme heat	2
			Heatwaves	2
	Compressor Valves and Regulators	Above-ground compressors, valves, and regulators may have high exposure to sunlight and heat, while indoor assets are shielded and may face slightly lower temperatures with proper ventilation.	Extreme heat	3
			Heatwaves	3
	Gas Importation Terminals	Gas importation terminals, typically situated in coastal regions, lack natural shading, and are directly exposed to high temperatures. However, they do benefit slightly from cooling sea breezes.	Extreme heat	3
			Heatwaves	3
Hydrogen	Hydrogen Electrolysers	Electrolyser and balance of plant may be exposed to heat, including compressors, pumps, pipes, separation units, and heat exchangers. Although exposure may be lower for some components, as most pipelines and valves are buried and therefore less exposed to sunlight.	Extreme heat	2
			Heatwaves	3
	Hydrogen Pipelines		Extreme heat	3

Asset categories	Asset	Exposure	Hazard	Vulnerability rating (1-5)
		Valves are most exposed due to manhole covers and access points for maintenance, with heat transfer potentially increasing pipe temperatures.	Heatwaves	3

3.3 Impact assessment

This section discusses the potential impact of extreme heat on generic energy asset types across the UK, under different warming futures. To assess potential impact, the qualitative vulnerability ratings (presented in Section 3.1) were combined with exposure ratings developed using the spatial projected extreme heat data (presented in Section 3.2) to form impacts scores. Figure 4 provides the matrix used to develop the impact scores. This approach is described in further detail in Annex A.3.1.

Figure 4 Potential impact matrix, combining ratings of exposure and vulnerability

	Associated temperature threshold (°C)						
Exposure	42+	5	1	2	3	4	5
	37-41	4	0	1	2	3	4
	32-36	3	0	0	1	2	3
	27-31	2	0	0	0	1	2
	Below 27	1	0	0	0	0	1
Potential level of impact			1	2	3	4	5
			Vulnerability				

The impact maps demonstrate the potential magnitude of impact under future GWL scenarios, *if* the asset is/will be located in an area. Spatial data on the location of energy assets was not used to map exposure of specific assets, given the lack of available data regarding asset location and the potential for changes in asset type and location under the changing energy system. Therefore, the information shown is useful for considering where extreme temperature impacts need to be considered, to inform future planning of the net zero energy system.

Figure 5 to Figure 7 below show the potential impact of extreme heat on energy assets that are qualitatively rated at a vulnerability level of 2, 3 and 4, respectively. No assets were identified as having vulnerability ratings of 1 or 5, hence only three maps are shown as key results. The maps show the difference in potential impact under different GWLs, reflecting the projected change in potential impact in a 1.5°C, 2°C and 2.5°C world. As discussed in Section 3.2.1, only the most extreme temperature projections (annual maximum air temperature for each GWL) are presented here. See Section A.3.2 for the full set of mapped results.

The relative level of impact is dependent on an asset's level of vulnerability and level of exposure. Therefore, potential impact is expected to be higher for assets with higher vulnerability, exposed to more extreme heat. As shown in Section 3.2, modelled extreme heat is trending higher under more severe future warming scenarios. Hence, an increase in impact is seen between GWL 1.5°C, 2°C, and 2.5°C.

Figure 5 maps the potential impact to **resilient assets** (rating of 2) at different GWLs. Assets (and asset categories) identified as being 'resilient' (rating of 2) include:

- Wind turbines (electricity generation)
- Gas transmission and distribution networks (electricity generation)
- Hydrogen electrolysers[7] (hydrogen)

Resilient assets (rating of 2) are expected to experience no impact at GWL 1.5°C. Low impacts are seen across areas of Wales, the Midlands, and Southwest under GWL 2°C, with more consistent low-level impacts seen across Southern England and the Midlands under GWL 2.5°C. Under GWL 2.5°C, low impacts are seen in smaller areas across the North of England and Scotland, with localised low-medium impacts in East Anglia. Under this analysis, resilient energy assets located across Southern England may experience low level impacts as global warming progresses, despite possessing resilient characteristics.

[7] Hydrogen electrolysers are 'potentially vulnerable' to heatwaves and 'resilient' to extreme heat.

Figure 5. Potential impact level for energy assets considered resilient (vulnerability rating 2)

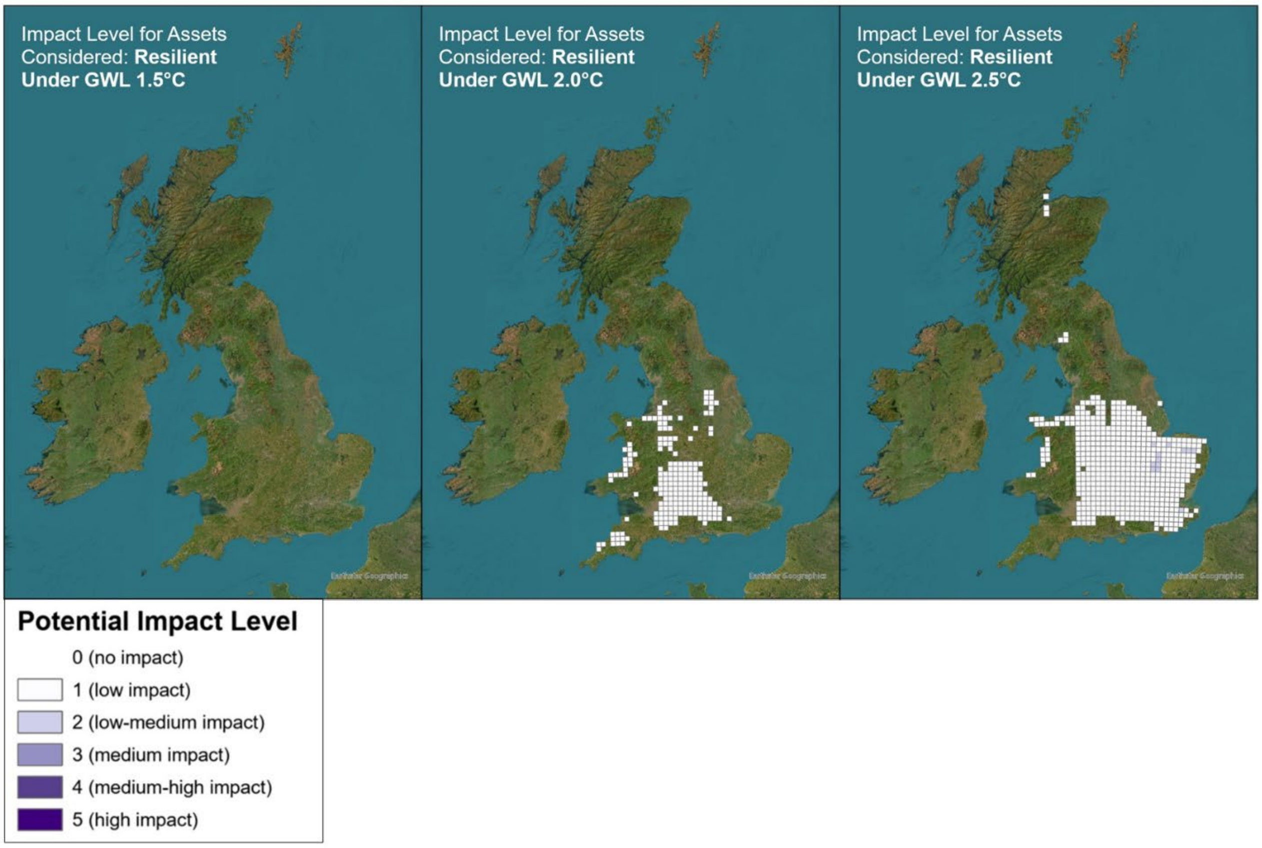


Figure shows the potential level of impact to **potentially vulnerable assets** (rating of 3) at different levels of warming. Assets (and asset categories) identified as being ‘potentially vulnerable’ (rating of 3) include:

- Gas power plants and CCS (electricity generation)
- Nuclear power plants (electricity generation)
- Solar panels (electricity generation)
- Hydropower (electricity generation)
- Overhead lines: transmission, distribution and HVDC lines (power networks)
- Power electronics, converters, filters, and interfaces (power networks)
- Control, monitoring and metering equipment (power networks)
- Distribution & transmission automation systems (power networks)
- Substation and network earthing systems (power networks)
- Battery storage systems (energy storage)
- Pumped hydro systems (energy storage)
- Compressed air energy storage (energy storage)
- Thermal energy storage (energy storage)
- Gas storage units (energy storage)
- Hydrogen storage units (energy storage)
- EV lithium-ion batteries (energy storage)
- Compressor valves and regulators (energy storage)
- Gas importation terminals (energy storage)
- Hydrogen electrolysers (hydrogen)
- Hydrogen pipelines (hydrogen)

Under GWL 1.5°C, we see low impacts across the majority of England, with localised low impacts in Wales and Scotland. As global warming trends progress, low impacts are also seen in Northern Ireland and Scotland. Under GWL 2°C, low-medium impacts are shown across the West and Southwest of England, parts of Wales, and the Midlands. Consistent patterns are seen under GWL 2.5°C, where potentially vulnerable assets located throughout the UK experience low or low-medium impact, with localised outcomes in East Anglia and Southeast England where assets could experience medium levels of impact. Based on this analysis, patterns emerge showing that potentially vulnerable energy assets may experience impact under GWL 2°C, regardless of location, and potentially vulnerable assets located in England may experience low-medium to medium impact under GWL 2°C and 2.5°C.

Figure 6 Potential impact level for energy assets considered potentially vulnerable (vulnerability rating 3)

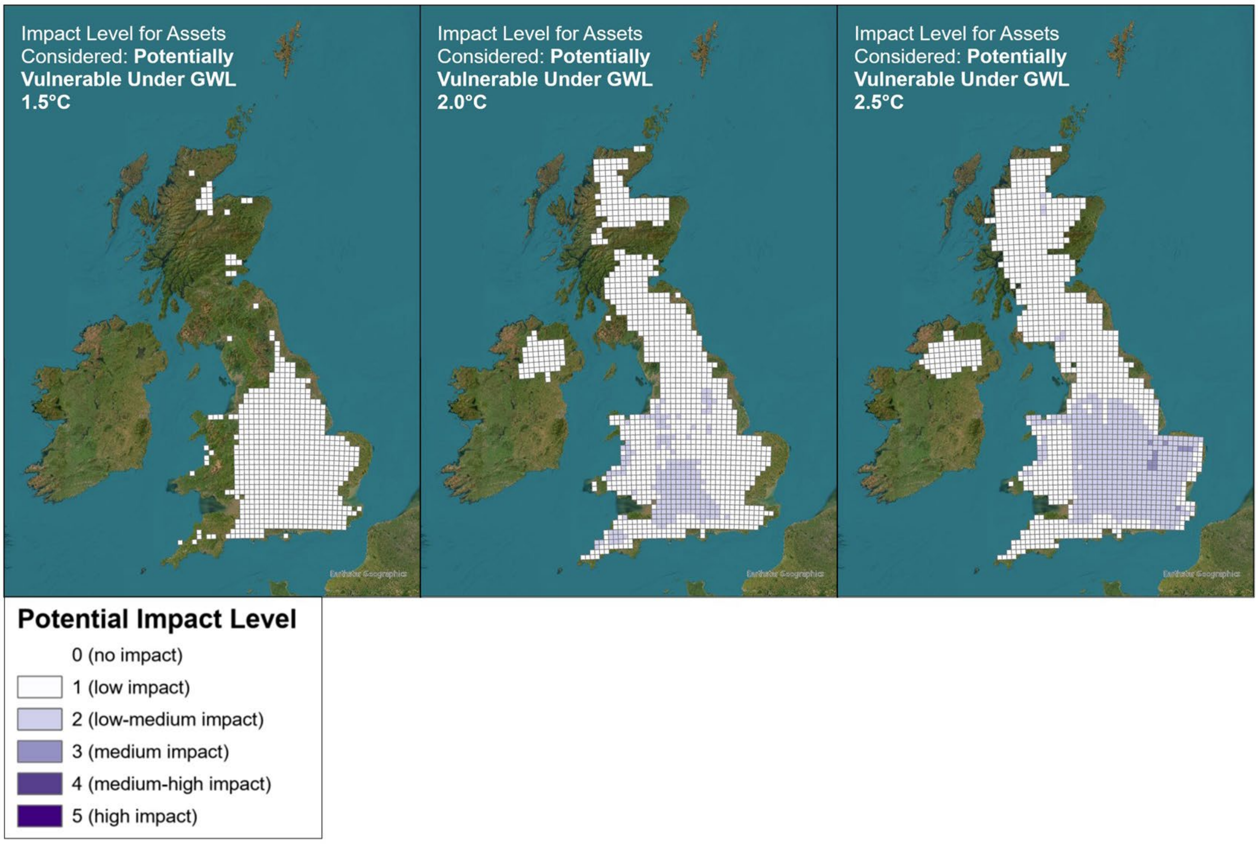
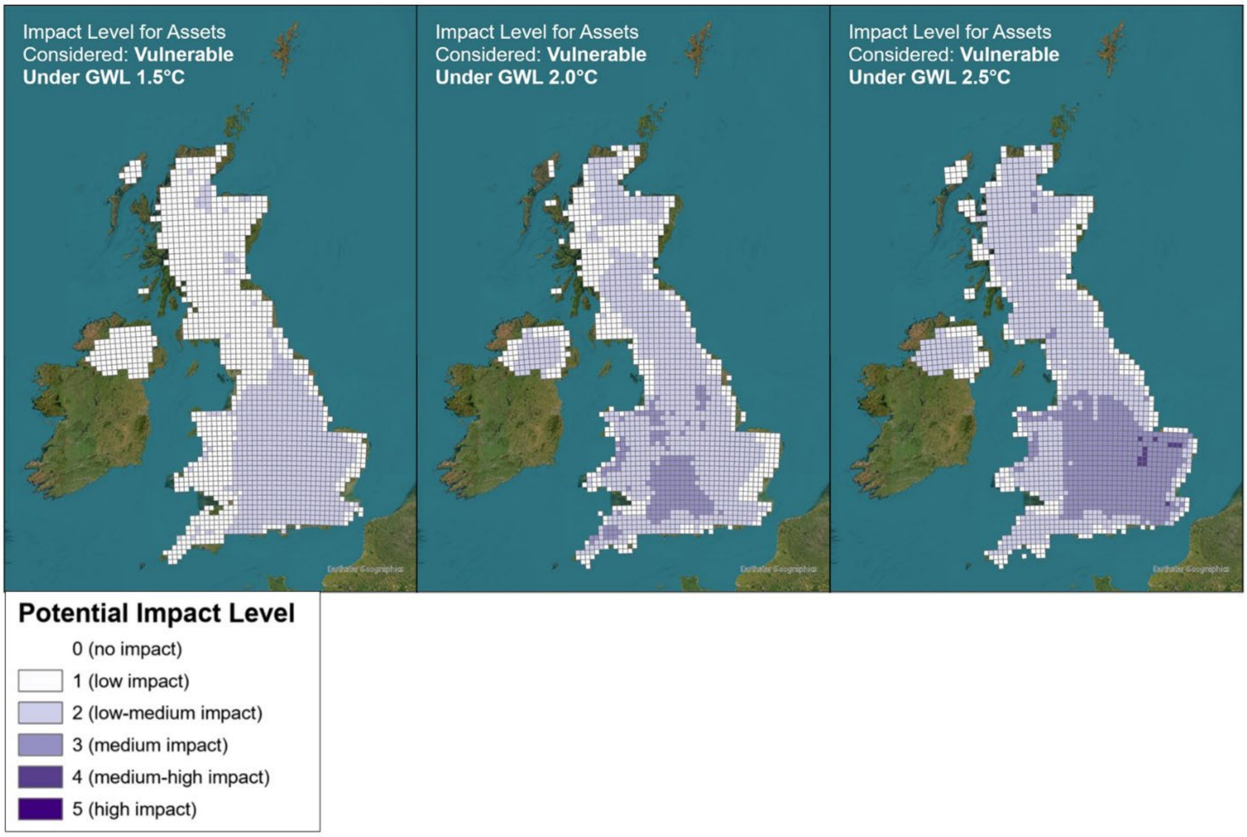


Figure 7 shows the potential level of impact to **vulnerable assets** (rating of 4) under different levels of waring. Assets (and asset categories) identified as being 'vulnerable' (rating of 4) include:

- Distribution underground cables (power networks)
- Transmission & distribution transformers (power networks)
- Service lines and connections (power networks)
- Switchgears, circuit breakers and other protection devices (power networks)

Under GWL 1.5°C, low impacts are shown across the majority of the UK, with low-medium impacts occurring across England and parts of Wales and Scotland. As global warming continues, GWL 2°C shows low-medium levels of impact more consistently across the whole of the UK, with medium impact occurring in the West, Southwest, and North of England, and parts of Wales. GWL 2.5°C is where vulnerable assets may experience the highest level of impact, with consistent low-medium impacts throughout the UK, medium impact concentrated across England (excluding the Southwest), and medium-high impacts occurring in East Anglia. This analysis shows there is a potential for vulnerable energy assets to experience impacts from extreme heat under all warming scenarios, with particular concentration of more severe impacts across England.

Figure 7 Potential impact level for energy assets considered vulnerable (vulnerability rating 4)



The results of the spatial analysis highlight the difference in experiences of extreme heat across the UK, with impacts to energy assets concentrated in England (due to the spatial concentration of potential future extreme heat occurrences). The variance in potential impact between assets with different levels of vulnerability also highlights the importance of building resilience within and across assets.

There are caveats and limitations to consider when using these results to inform the location and design of future energy assets. Firstly, as this impact assessment is partly based on the maximum air temperature data used in the exposure assessment, through the combination of this data and the vulnerability scores, the key uncertainties outlined for the exposure assessment (in Section 3.2.2) apply here too.

Additionally, it is important to consider that 'impact' refers to different potential impacts on generic assets that are rated at the different levels of vulnerability. To contextualise these results, Box 1 describes the impact that the 2022 heatwave had on the UK energy system.

The nature of this impact will differ depending on the design of the energy asset and whether adaptive measures (cooling, insulation, etc.) are taken.

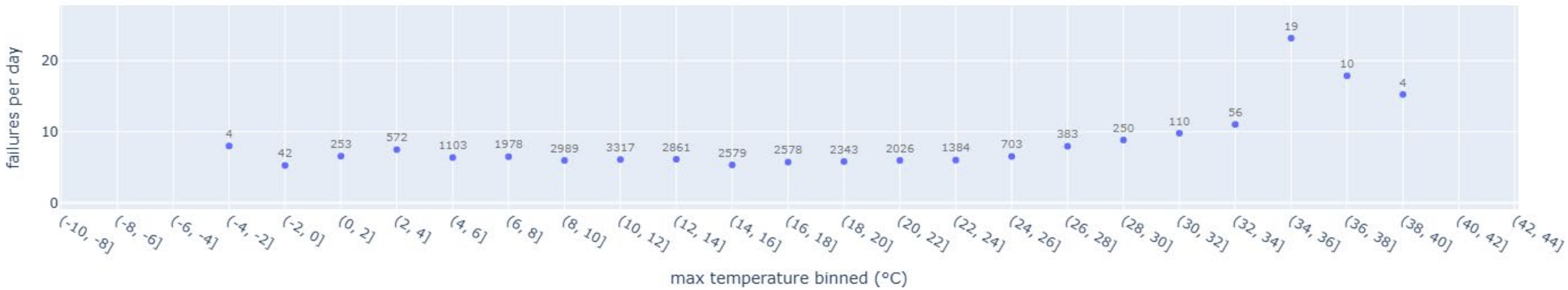
Box 1: The impact of the 2022 heatwave on the UK energy system
The temperatures reached during the July 2022 heatwave were similar to the maximum projected outcome at the2°C GWL [2]. Despite the power grid, as a whole, experiencing significant stress, the system-wide impacts were low-medium [3]. At the asset level, the impacts varied. Some components experience higher levels of impact and failure. The BBC reported that extreme temperatures approaching 40 °C caused some assets to overheat, leading to almost 15,000 properties in Yorkshire, Linconshire and the North East losing electricity, some of them overnight from July 18-19. Northern Powergrid reported an abnormally high number of faults, which caused delays in the power being restored [4]. In addition, the UK came close to a shortfall in electricity supply, not as a result of power plant failures, but rather the degraded output and effectiveness of power plants and transmission lines. Wholesale electricity prices surged as the UK was forced to import power from Europe at a high cost. Currently, approximately ~5% (likely below) of UK households have air conditioning. In the future, as people adopt active cooling technologies, reductions in electricity demand induced by extreme temperatures may coincide with higher spikes in electricity demand, exacerbating the risk of supply shortfalls [3]. This risk is explored further in Section .

3.4 Predicting temperature-related energy faults

To corroborate the findings from the vulnerability, exposure and impact assessments presented above, an exploratory quantitative analysis was conducted using real-world data from the UK to explore the relationship between ambient temperature and power system electrical faults in the UK. Beyond triangulating the findings from other sections, this exercise aimed to understand what machine learning methods can tell us about the relationship between temperature and faults based on real data. The methodology is explained in Appendix 4.

Using the National Fault and Interruption Scheme (NaFIRS) dataset, which contains DNO-related network faults, the relationship between maximum temperature and network faults was explored. Figure shows the average number of faults taking place on a day where the maximum daily temperature is in a given 2-degree interval. It has been normalised by dividing the number of faults occurring in a given 2-degree temperature interval by the number of days in each temperature interval. The numbers above each data point is the number of days in a given temperature bin. Figure shows that the fault rate is between 5 and 10 faults per day between the interval -4 to +30 °C, and then increases above 10 faults per day for temperatures above 30 °C.

Figure 8 Number of faults per day in each temperature interval.



Based on the increased fault rate at high temperatures in the distribution network, supervised machine learning methods were explored to predict the faults based on weather-related variables. The feature dataset included the maximum daily temperature, minimum daily temperature, daily rainfall, and additional engineered variables from these three variables. Data for 2018 to 2022 was divided into training and test samples, with80% of the data used to train the model and 20% reserved for validation. More details are provided in Appendix 4.

Multiple models were tested and Extreme Gradient Boosting (XGBoost) was chosen as the best performing machine learning model. See Appendix 4 for more details on the data and the specification of the model.

The dataset contains fault cause categories, but due to uncertainty around which cause categories are directly or indirectly affected by heat, the dataset was not filtered by specific cause categories. Also, the dataset does not contain data on what actions DNOs have taken to reduce faults. As the model is trained on historical data, predictions do not take into account future adaptations that DNOs could implement to reduce faults in response to increasing temperatures, and thus there is uncertainty regarding what the true fault rate will be in the future.

Figure shows the model's performance in predicting fault rates as a function of temperature compared to actual unseen test data. The model predictions are reasonable, but the accuracy is limited at higher temperatures due to the limited data available for days >30 °C and the quality of the datasets used to train the model.

Figure 9 Prediction and ground truth in the High Voltage test dataset

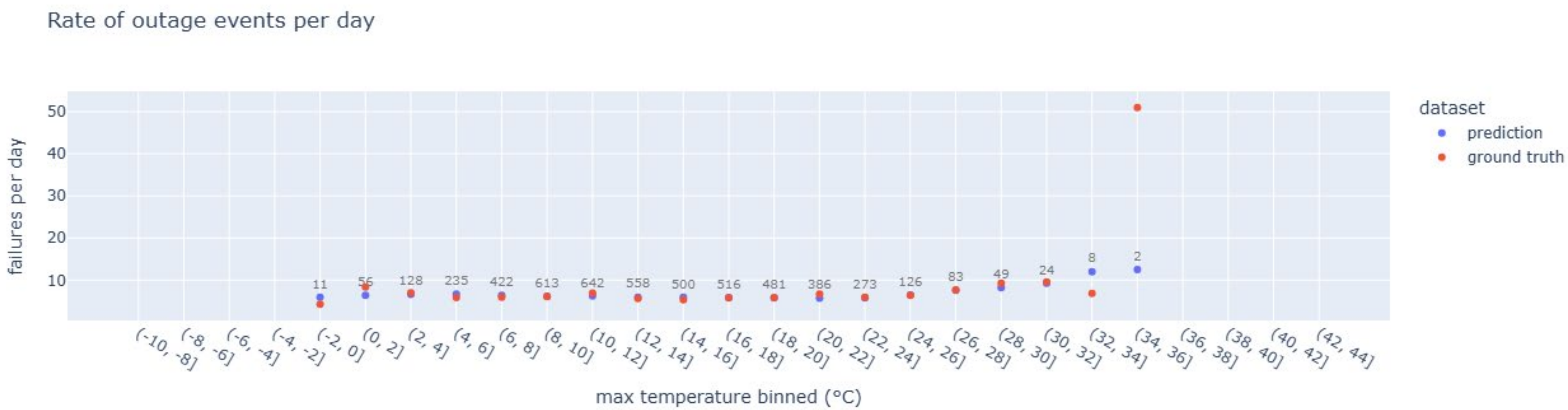


Figure 10 below shows the predictions on their own with an adjusted axis. The figure shows that the model is predicting an upward sloping relationship between daily maximum temperatures and faults at temperatures above 20°C.

Figure 10 Prediction in the High Voltage test dataset (identical to Table 9, with axis adjusted for easier inspection)

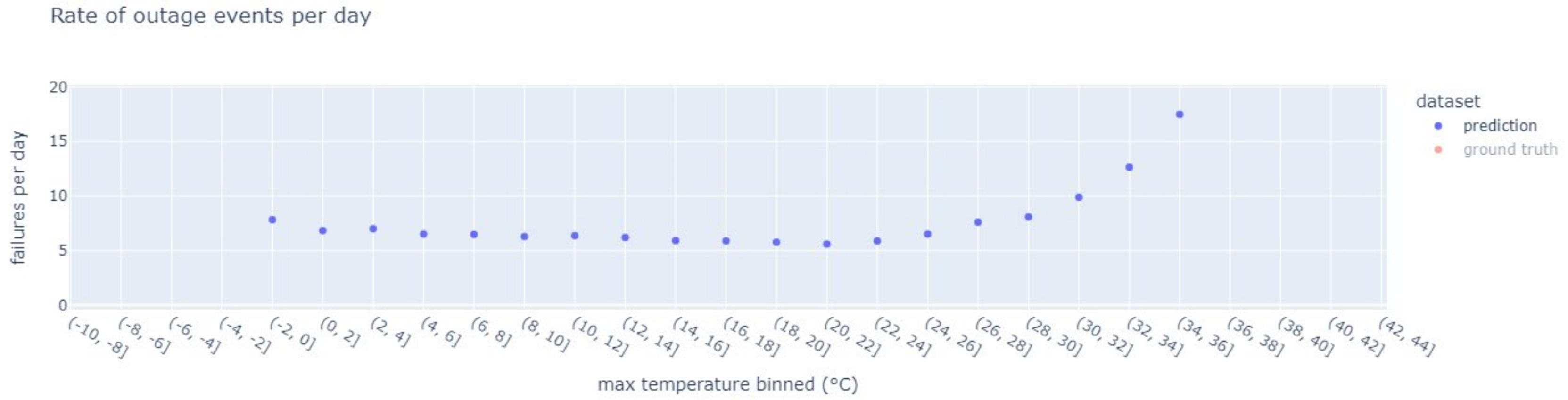


Figure 10 above shows the same predictions as in Figure 9, but without the ground truth comparison, and with an adjusted axis to inspect the predictions more clearly. It shows fault rate the model is predicting at each temperature threshold.

In conclusion, there is evidence of an increased fault level at higher temperatures. Faults increase in frequency above 30°C. This corroborates to some degree the Vulnerability and Impact findings. However, there was insufficient historical data to accurately quantify this relationship at higher temperatures. Machine learning techniques were useful where there was a clear correlation between temperature and faults, such as the HV network faults data. Recommendation for further work is to incorporate additional data from countries with hotter climates to improve the robustness of the results above 30°C.

3.5 Extreme heat and the UK's future energy demand

In addition to the direct impacts of thermal stress on energy system assets, various climate change driven extreme heat and heatwave events may lead to increased indirect stress on the electricity system through increased demand for active cooling (air conditioning, heat pumps etc.). The increased loading on electricity networks caused by active cooling may coincide with the periods of direct impact on the energy system discussed in the previous sections. As described previously in Box 1 on the impact of the July 2022 heatwave, these factors may compound to increase the likelihood of electricity shortfalls and loadshedding.

A literature review was carried out to examine how well these potential indirect impacts are currently understood, and what potential mitigation and/or adaptation options might be applied to reduce future indirect risks. The results can be found in A.5.1.

In the UK, cooling currently estimated to represent 3% of energy demand, and 10% of electricity demand, and this is primarily driven by non-domestic buildings. However, significant growth is expected in domestic cooling demand, driven by rising temperatures and increasing adoption of heat pumps for heating and cooling as part of the UK's decarbonisation strategy [5]. There is little agreement on the size or timing of this increase.

In 2021, the Department for Business, Energy and Industrial Strategy (BEIS) published a research paper that assessed cooling energy demand and uptake scenarios based upon two climate warming scenarios (+1.5°C and +4°C) on cooling demands [6]. In the highest scenario, the study found that peak cooling power consumption for the UK may increase from roughly 12 to 19 GW in 2100. The Domestic Air Conditioning 2050 project by the UK Energy Research Centre [7] also assessed the impact of a number of scenarios of air conditioner adoption on electricity demand. In the highest scenario, UKERC projected that air conditioner adoption would increase the evening peak by 7 GW by 2050. Several other studies, such as the "Updated energy and emissions projections 2021 to 2040" [8], provide insight into cooling demand under different climate scenarios, and the results vary widely due to differing assumptions about the rate of active cooling uptake, the efficiency of the units, etc. The studies often overlook the adoption of heat pumps and their dual heating-cooling functionality, which could act as a key factor driving growth in cooling demand. This research gap creates uncertainty around future cooling demand trends and the impact on electricity systems.

While summer cooling demand may exacerbate summer peak electricity loads, it is assumed the UK grid should have adequate capacity to meet this increase. Historically, annual peak demand occurs during the colder winter months owing to seasonally inflated utilisation of electrified heating. The loading on the electricity system due to this winter peak is expected to remain significantly greater than any new summer peak resulting from new cooling demand, because the UK plans to electrify a large portion of its heating demand in the coming decades. This suggests that sufficient capacity should already be built into the electricity system to comfortably accept this additional cooling load. However, this reasoning does not factor in the risk that during a heatwave, peak cooling demand (which may have geographical concentrations) is likely to coincide with a reduction in the efficiency across the electricity system, as discussed in previous sections. Moreover, summer peak demand for cooling may occur in the evening, and not coincide with peak solar PV production. If peak demand coincides with a period of low wind generation, it could present a challenge for a system with a generation mix dominated by variable renewable electricity.

Potential adaptation options should consider continued expansion of grid flexibility through the deployment of storage, dispatchable generation, and interconnections, as well as promoting energy efficiency via passive cooling measures like insulation, improved ventilation, and demand side response. District heating and cooling systems, which are widely utilised in Scandinavia, could offer valuable insights for the UK and inform a more joined up heating/cooling strategy; however, these examples may not be easily transferable and would require in depth assessment.

3.6 Asset specific adaptation options

This section investigates potential options to address extreme heat across energy assets. Strategies such as cooling technologies and infrastructure modification are explored, considering feasibility and effectiveness in ensuring readiness to heat-related challenges.

A range of adaptation measures, identified within literature, were analysed to determine their effectiveness in reducing energy assets' vulnerability and exposure to extreme heat and heatwaves. This exercise does not seek to provide an adaptation plan; these measures have been collated to demonstrate existing recommendations and illustrate ways in which vulnerability and exposure can be reduced, and resilience built. The full range of measures identified within existing literature is detailed in section A.6.2. **Seven key measures,** that are common across asset categories, are highlighted below. Of the 7 common measures, six reduce sensitivity to extreme heat and enhance adaptive capacity, 1 measure addresses exposure.

1. **Selective undergrounding of power network lines:** The singular measure identified that reduces exposure is using **selective undergrounding of power network lines**. This delivers a reduction in exposure to extreme heat by relocating lines and connections below ground, where temperatures are more stable in response to surface solar radiation. This might introduce other issues to power systems such as increased costs of development (being generally 3 to 5 times more expensive than overhead lines and could be more than that depending on particular site [Ricardo in-house experts]). An increase in complexity of maintenance would also be associated with increased costs, although the frequency of maintenance that is required may be reduced overall.
2. **Upgrading cooling systems:** Upgrading cooling systems to withstand projected temperatures can be applied to the greatest number of vulnerable assets. While upgrading cooling systems potentially results in greater energy consumption and additional equipment, the overall GHG impact must be assessed from a lifecycle approach. Operators will inevitably need to refit cooling systems and therefore could evaluate the GHG emissions and cost-benefit of doing so within earlier timeframes to mitigate extreme heat. If the upgrades extend the lifespan of the infrastructure, long term emissions reductions may contribute to mitigation efforts while addressing extreme heat. The scale of cooling requirements will depend on multiple factors, with energy and emissions implications varying accordingly. A full lifecycle assessment would provide a clearer understanding of these impacts.
3. **Automated monitoring and controls:** This can also help to keep track of real time operating conditions, which can be used in combination with smart controls to make. remote changes such as reducing the allowable current or turning on advanced cooling measures. These can keep temperatures below the design threshold and minimise the impact on network operation under extreme heat. A potential issue associated with this adaptation option is that automation and real-time tracking systems are susceptible to

cyberattacks, which could compromise both the energy assets and wider grid stability. Co-benefits include the facilitation of faster response and recovery times, improving system reliability.

4. **Incorporating upgraded insulation:** Incorporating upgraded insulation into a system could be used to reduce temperature fluctuations, therefore reducing cooling system workload. By creating a barrier that minimises the transfer of external heat into systems, and shielding components from heat stress, this adaptation option would reduce cooling system workload and prevent heat-related pressure changes.
5. **Installing ventilation:** Ventilation can be installed to reduce sensitivity by allowing airflow to dissipate heat more effectively, preventing overheating of critical components. This can allow assets to achieve their intended design life and prevent accelerated degradation, avoiding greenhouse gas emissions generated by the manufacture of new assets. While passive ventilation is relatively lower in cost, active ventilation techniques may be more effective but also involve the emission of greenhouse gas emissions. However, as temperatures rise, passive ventilation may become less effective relative to overall cooling needs. In such cases, active ventilation may be required to maintain performance, though this comes with energy and emissions trade-offs.
6. **Installing shading:** Shading reduces the impact of extreme heat by lowering surface temperatures, minimising heat absorption that can cause damage to infrastructure and thereby reducing sensitivity to extreme heat. Implementing this adaptation measure would help to mitigate accelerated degradation caused by direct sun exposure and minimise the need for premature replacements. Alternative measures should be implemented to reduce vulnerability of assets to the impacts of high ambient air temperatures.
7. **Upgrading to heat resistant materials:** This would involve replacing components with technology that can withstand prolonged exposure to significantly higher temperature thresholds. This would improve the durability of materials predominantly used in electricity generation, power network and energy storage asset categories. Retrofitting structures would help to avoid complete reconstruction and could be aligned so that material upgrades take place within the existing renovation cycle.

These seven measures constitute high level options that are common to multiple asset categories. The timing, cost of implementation, risk of maladaptation and co-benefits were key factors analysed to provide a holistic view of the utility of the option. Power networks and energy storage systems were found to benefit from the greatest number of measures. In contrast with this, relatively fewer common measures were identified that address hydrogen and natural gas infrastructure.

4. Conclusion

This study sought to enhance the understanding of the vulnerability and exposure of generic energy assets within the UKs energy system to extreme heat and heatwaves and shed light on potential impact. It generated a number of insights, which are presented below as key takeaways, evidence gaps, and potential further analysis.

While useful, these insights contain significant uncertainties and should be closely considered in context with the associated evidence gaps and limitations. . This report seeks to do that by offering results with clear opportunities for further research, which may help DESNZ and other decision-makers to identify future research priorities and to consider the resilience of energy assets within the design of a net zero energy system.

4.1 Key takeaways

4.1.1 Vulnerability

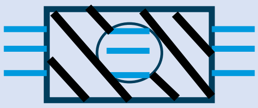
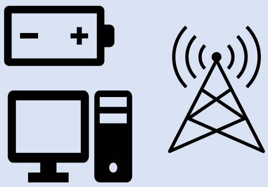
Based on evidence identified through REA and critical analysis, our study identified the relative vulnerability of generic energy assets and asset categories to extreme heat. Table 1presents these results in order of vulnerability, from most to least vulnerable. Overall, the most vulnerable asset category was power sector networks. Several components were rated vulnerable (rating of 4), including distribution underground cables, T&D transformers, service lines and connections and switchgears, circuit breakers and other devises. Increasing the resilience of these vulnerable assets should be a priority for adaptation efforts. Specific vulnerabilities for each asset have been identified in Section 3.1.

Several direct vulnerabilities to extreme heat were common across different types of assets; notably, **decrease in efficiency and performance**, **mechanical degradation due to**

thermal expansion, an **inability to effectively dissipate heat**, and therefore an **increased reliance on cooling to prevent overheating**. Evidence also highlights two indirect vulnerabilities relating to the **effect of extreme heat on workers and other assets** within the energy network, which affect the resilience of assets through their operational function. A list of these common 'key vulnerabilities' to extreme heat is presented in Table 7.

Table 7 Key findings of vulnerabilities and vulnerability outcomes across energy assets and asset categories

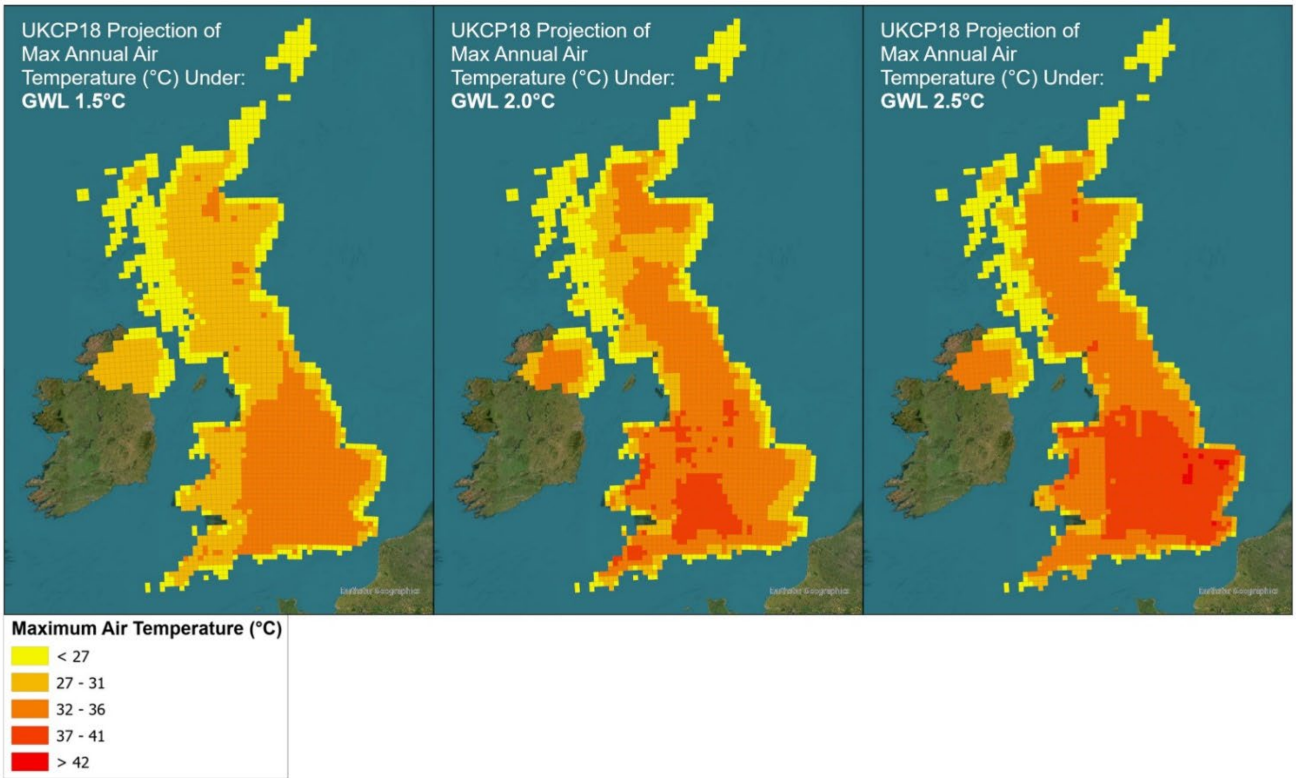
Vulnerability outcome	Vulnerability
Efficiency decrease	Extreme heat can reduce the efficiency of systems due to impact on air density, water temperature, and increased demand for cooling that affects overall system efficiency.
Capacity derating	Extreme heat may prevent efficient heat dissipation which causes the operating temperature to rise and reduces the margin to the design temperature. Hence, assets need to be operated below the rated capacity to prevent accelerated degradation and shortening of life.
Thermal expansion and mechanical degradation	Extreme heat can cause thermal expansion of the metal parts leading to reduction of tensile strength, excessive stress on joints, accelerated degradation of metal components that affects the mechanical strength over the long run.
Cooling challenges	Extreme heat may put excessive strain on cooling systems due to increased demand for cooling to maintain the optimum operating temperature of assets. This overwhelms cooling systems and reduces system efficiency, if unable to cope with

Vulnerability outcome	Vulnerability
	increased demand it can lead to decreased efficiency, shutdowns, or failures.
 **Insulation degradation**	Extreme heat could lead to insufficient heat dissipation, causing the operating temperature to exceed the design temperature of the insulation, which can result in insulation degradation, impact operation and pose a safety risk.
 **Maintenance & reliability issues**	Extreme heat complicates maintenance efforts and risks worker safety. Prevention of maintenance increases the risk of cascading failures due to the interconnected nature of equipment.
 **Supporting systems performance**	Asset reliability could be impacted not only due to assets own degradation but also due to the reduced performance of supporting systems. Extreme heat can affect the performance of supporting telecom and communication infrastructure, primarily because of the heavy reliance on batteries, whose performance can be significantly impacted if not maintained properly.

4.1.2 Exposure

Spatial analysis of UKCP18 projections demonstrated that the UK's energy system is expected to be exposed to increased levels of extreme heat under future warming scenarios. Extreme temperatures are projected to occur across the UK under each GWL. The most extreme temperatures are concentrated throughout England and parts of Wales (see Figure 11). Under the highest GWL (2.5°C), the south of England is projected to be exposed to temperatures of up to 42°C, with the rest of the UK (excluding coastal areas) projected to experience maximum temperatures of up to 36°C.

Figure 9 UK-wide exposure to extreme heat under GWLs 1.5 °C, 2 °C and 2.5 °C



4.1.3 Impact

Assets rated as vulnerable may experience impacts from extreme heat under all warming scenarios. Under GWL 2.5°C, the highest scenario considered in this analysis, low-medium impacts may be expected throughout the UK, with medium impacts concentrated across England (excluding the Southwest) and medium-high impacts occurring in East Anglia. The nature of this impact will differ depending on the design of the energy asset and whether adaptive measures (cooling, insulation, etc.) are taken.

These findings were partially corroborated through a quantitative analysis of real-world data from the UK that identified a historical correlation between the exposure of the UK electricity system to extreme heat and fault rates. Faults have historically increased in frequency above

30°C. There was insufficient historical data to accurately quantify this relationship at higher temperatures.

The asset-level impacts identified in this study may or may not translate to system-wide impacts. The added resilience from diversity and redundancy in the system was not factored into the analysis. The cascade of impacts from one asset to another, or from one asset into system-wide impacts, were not accounted for in the assessment. Compounding impacts, such as the impact from multiple assets experiencing increased faults or reduced efficiency and output were also not considered in the spatial analysis.

To supplement the analysis on direct impacts from extreme temperatures to energy system assets, a literature review was conducted on whether the UK electricity system will experience indirect stress on the electricity system through increased demand for active cooling (air conditioning, heat pumps etc.). It found that the UK will likely add sufficient generation capacity to meet summer peaks in demand for cooling, given that these summer peaks are likely to be lower than winter peaks if the UK follows through with electrification of heating and transport. However, the increased loading on electricity networks caused by active cooling may coincide with the periods of direct impact exposures on the energy system. These factors may compound to increase the likelihood of electricity shortfalls and loadshedding. Policymakers are encouraged to include cooling demand in future decarbonisation considerations. By developing a better understanding of this topic, future policy decisions could enhance efficiency, support the future proofing of electricity networks, and ensure optimal long-term solutions are developed.

4.2 Evidence gaps remaining

In reviewing available data and evidence for the assessments conducted in this study, gaps were identified that, if addressed, could strengthen the analysis and help build a more comprehensive mapping of climate risk to energy assets.

- **Relationships between assets and extreme temperatures**: To determine the vulnerability of energy assets to extreme heat, the REA sought to identify information explaining the sensitivity of assets to temperature changes and the capacity for asset owners to manage these sensitivities. In some cases, only a limited number of studies that explored this relationship were available; in particular, relating to energy storage, hydrogen, and natural gas infrastructure. The absence or presence of studies does not indicate a lack or presence of vulnerability or resilience, respectively. In all cases, literature was supplemented with expert judgement and stakeholder consultation. Nevertheless, additional research into the relationship between energy assets and extreme temperatures would strengthen the confidence in findings.

- **Asset location, characteristics and redundancy**: The lack of readily available database regarding existing and planned energy sector assets and their characteristics prevented the study from identifying the vulnerabilities and projected impacts for real-world assets. It also limited the ability to assess system wide vulnerabilities, determine the potential for cascading and compounding impacts, and prioritise interventions. Available data showing the type of assets in service, where they are located across the UK, their connectivity and interdependency with other assets, and level of redundancy would enable better planning for extreme events, by helping to target single-points-of-failures and prevent faults and enabling prioritisation of upgrades towards the future net zero system. It would also provide a better picture of system wide resilience.
- **Asset temperature thresholds**: Through the REA, design thresholds for temperature were identified for some assets. This information helps to determine the point at which assets behave optimally or experience impacts from temperature fluctuations. However, current information is inconsistent across assets and asset categories. More consistent data on the temperature thresholds across assets would be needed to accurately quantify vulnerabilities and impacts across the system.
- **National fault data**: This study used National Fault and Interruption Scheme (NaFIRS) data to determine the relationship between faults and temperature, and to predict temperatures at which faults will begin to increase. The NaFIRS dataset is useful, but imperfect. According to sector experts, the process for recording faults may not always accurately identify the cause of a fault, or the environmental or weather conditions in which they occurred. Improvements to national fault recording, specifically by including the ambient air temperature at the location where the fault occurred, would enable more accurate identification of drivers of faults and more clearly demonstrate the relationship

between faults and temperature. Research on the quantitative relationship between temperature and other asset classes, beyond distribution networks (such as generation assets and transmission network) would also be beneficial as this would provide a clearer understanding of impact from temperature across the system.

4.3 How this research can be built on

The evidence generated in this study can be used as a baseline from which to build a more comprehensive and valuable picture of energy system resilience.

- **Quantitative analysis of asset responses to temperature**: This study qualitatively rated the vulnerability of generic energy assets, with temperature design thresholds considered only where they were available. Exposure was rated only through the projections of extreme heat, given a lack of available data regarding asset location. These ratings were combined to generate an overall 'potential impact' rating. However, each asset type will respond differently to temperature thresholds being exceeded. This relationship will not be uniform or necessarily linear as assumed in this study. A more quantitative approach would analyse impacts to specific assets with different technical specifications, and their specific exposure to extreme temperature, generating an understanding of specific impacts (reduced efficiency, occurrences of faults, damage, etc.). Such a study would require more comprehensive data on the location of each asset and their specific temperature thresholds and sensitivities.
- **Integrating lessons from other geographies**: This study explored the relationship between energy assets and future projections of extreme heat within the UK. However, extreme heat is already a common occurrence in many parts of the world. As we move towards a hotter climate, knowledge can be gained from countries with more experience ensuring energy security under extreme conditions. This may consist of sharing lessons on national fault data, engineered interventions, system design, operational planning and preparedness, and incident response mechanisms.
- **Cascading and compounding impacts**: This study has compiled information regarding the relationship between energy assets and extreme temperatures within the UK, demonstrating potential impacts under different future scenarios. It has not been able to

analyse the potential compounding outcomes from impact to multiple assets, or cascading impacts from one affected asset to another. This analysis is critical for understanding risk to the whole energy system and for prioritising areas of action by identifying single points of failure, thereby ensuring energy security under a changing climate. This could be done by addressing the aforementioned evidence gaps and building on the assessment of asset vulnerability, exposure, and impact, generated in this study.

- **Detailing and prioritising adaptation measures**: The final component of this study collated potential adaptation measures that could reduce energy asset vulnerability or exposure to extreme heat. The exercise was not intended to provide a plan for adaptation interventions, but to summarise and reflect existing approaches to preparing assets for extreme heat, illustrating steps that could be taken to build resilience. More specific studies are required to determine key implementation details (including feasibility, cost-benefit, timeline/urgency, responsible authorities, etc).

5. Appendices

Appendix 1 – Vulnerability Assessment

A.1.1 Methodology

This section describes in detail the methodology that was used to assess the vulnerability of energy sector assets to extreme temperatures. Vulnerability is the *predisposition* of an asset to experience negative consequences from an external factor. Table 8 below provides the IPCC AR6 definitions of key terms involved in vulnerability assessment.

It is key to note that vulnerability to extreme heat and heatwaves was assessed against the defined threshold of 27°C for extreme heat (outlined in Section 2.1.2). While the MO definition of heatwaves varies across the UK, the use of this threshold is in context of the local climate and how heat is experienced. In the context of energy assets, temperature is less 'subjective' in that heat would affect the same asset in the same way whether it was in the North or South of the UK. Therefore, the same temperature threshold was set for heatwaves and extreme heat, under the assumption that heatwaves consist of more than one consecutive day of extreme heat.

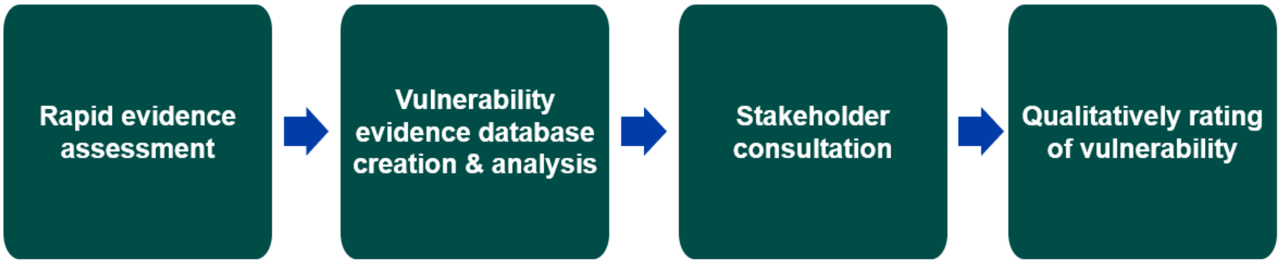
Table 8 Definitions of key terms associated with climate vulnerability, exposure, and impact, as per IPCC AR6

Term	Definitions
Vulnerability	Vulnerability is the tendency of people, ecosystems and species, economic, social, and cultural assets, and services to be affected by climate-related hazards. It is a product of sensitivity and adaptive capacity.
Sensitivity	The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
Adaptive capacity	The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. Adaptive capacity can be understood through four key components, defined by ISO standard ISO14091 ('Adaptation to climate change — Guidelines on vulnerability, impacts and risk assessment'): • **Organisational capacity:** The extent to which an organisation can factor adaptation to climate change into their decision-making processes, identify and

Term	Definitions
	deliver meaningful responses, and monitor, update and improve responses over time. Organisational capability is a product of a number of interconnected factors, which can include human resources, awareness, knowledge, interdependences, roles and responsibilities, leadership, policies and procedures, operational management, learning, motivation, interested parties, and legal requirements. • **Technical capacity:** The extent to which existing or new technologies can contribute to enhancing adaptation to climate change in the future. Technical capacity can be viewed as a component of organisational capability, but in some cases, it is better to view these separately. Technical capacity is a product of several factors. These factors can include technological resilience, interdependencies, and available options. • **Financial capacity:** The extent to which financial resources can be mobilised to ensure adaptation actions can be identified, implemented, and updated over time. Financial capacity can be viewed as an integral component of organisational capability. However, it can be valuable to assess it separately. Financial capacity is a product of several different factors. These factors can include evaluation (the extent to which an organisation can evaluate the benefits of adaptation actions against the cost), availability of funds, and mobilisation of funds. • **Ecosystem capacity:** The ability of natural and managed ecosystems to adapt to the impacts of climate change. Human actions can either further strengthen or undermine ecosystem capacity. Ecosystem capacity is particularly relevant to an organisation involved in natural resource management, such as the agriculture, fishery, tourism, and forestry sectors. Ecosystem capacity affects the provision of key ecosystem services on which humans depend (e.g. clean water, food, clean air, medicine). Enhanced ecosystem capacity can also mitigate climate change risks for an organisation, e.g. through water retention in wetlands that can function as a natural barrier to floodwater.
Exposure	The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.”
Hazard	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystem, and environmental resources
Adaptation option	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.

The process for conducting the assessment of vulnerability of energy assets is shown in Figure 10 :

Figure 10 Vulnerability assessment process overview



1. **Rapid evidence assessment (REA):** This step involved carrying out literature searches, identifying relevant literature and extracting evidence pertaining to asset vulnerability (sensitivity to extreme heat and adaptive capacity) and potential adaptation options to extreme heat.
2. **Vulnerability evidence database creation and analysis:** Key findings from the REA were extracted, reviewed and organised into a VRA evidence database. It included findings on sensitivity and all different component of adaptive capacity (organisational, technical, financial and ecosystem adaptive capacity. The gaps on REA findings were filled by Ricardo in-house experts.
3. **Stakeholder consultation:** This step involved validating the REA findings and addressing any remaining gaps by gathering input from stakeholders, facilitated through a survey created using the Alchemer platform. Overall, 64 stakeholders were contacted, of which 22 stakeholders participated in the final survey, consisting of 9 stakeholders from ‘Power Networks’, 4 from ‘Electricity Generation’, 4 from ‘Energy Storage’, 4 from ‘Hydrogen’, and 1 from ‘Natural Gas’, a detailed breakdown of stakeholders included by the consultation is shown in Table 11 below.
4. **Qualitatively rating of vulnerability:** A team of 3 experts, rated the vulnerability (on a scale of 1 to 5) based on the inputs from REA, stakeholders, and Ricardo experts. Ratings were sent for review to new castle university and any feedback were incorporated.

A.1.1.1 Rapid evidence assessment

A REA was conducted to identify existing evidence of energy asset vulnerability and exposure (including drivers and characteristics) to extreme heat and heatwaves. REA offers a systematic, comprehensive, transparent, and replicable approach for identifying evidence on the specific topic, ensuring evidence presented is robust and valuable.

The REA protocol that was followed in this study was:

1. Google Scholar was used for the academic literature searches. Where identified papers were not open access, they were retrieved via Ricardo's subscriptions to a range of academic journals, or, where necessary, through the study partners' subscriptions to specific journals.
2. Grey literature searches focussed on the online publication repositories of DESNZ, Defra, the CCC, UK National Grid, OFGEM and the International Energy Agency (IEA), alongside any further sources recommended by the PSG and subject-area experts. Grey literature searches were conducted with particular emphasis on assets for which limited information was found in Google Scholar searches.
3. The list of energy assets (shown in Table 9) to be analysed and reviewed for the impact of extreme waves was finalized in consultation with University of Newcastle. Initial search terms (summarised Table 9) for each asset class was developed and refined in consultation with university of new castle. Searches were then conducted to identify relevant literature using these search terms. These search terms were continuously monitored and refined throughout the search process based on the results retrieved. If a specific asset class appeared underrepresented in the initial search due to the presence of dominant terms within the search string, additional targeted searches focused on those individual assets were conducted. This was followed to ensure comprehensive coverage of the impacts of heatwaves and extreme heat events on the full range of energy assets under consideration.
4. A structured approach was employed to ensure a methodical and transparent search for evidence. This approach utilised relevant keywords and specific search techniques to form search queries. These search queries were constructed with three main elements:
   a. **Components/assets of the energy system:** Grouped into different classes, such as electricity generation, power network components, etc. or individual assets like solar power plant, wind power plant)

b. **Climate-related terms:** Focused on terminology connected to climate change and its implications, such as climate change, climate vulnerability, climate impact, and climate adaptation.

c. **Heat event-related terms:** This part of the search string included terms related to heat events, such as extreme heat event, heatwave, or high temperature.

The initial search terms for different classes of energy assets that were investigated in this study are shown in Table 9. As noted above, these were continuously monitored and refined in an iterative manner to ensure the highest quality results possible.

Table 9 Search term for different classes of energy assets

Energy asset category and key components	Search term
Electricity generation • Gas power plants and CCS • Nuclear power plants • Solar panels • Wind turbines • Hydropower	(Climate change OR vulnerability OR risk OR adaptation OR sensitivity OR capacity OR resilience) AND (extreme heat event OR heatwave OR high temperature) AND (wind turbine OR wind farm OR wind power plant OR solar panel OR solar power plant OR hydropower OR hydroelectric facility OR nuclear power plant OR (gas power plant OR CCGT OR CCS))
Power networks components • Overhead Lines (transmission, distribution, and HVDC lines) • Distribution underground cables • Transmission & distribution transformers • Service Lines and connections • Switchgears, circuit breakers and other protection devices • Power electronics • Converters • Filters and interfaces • Control, monitoring, and metering equipment. • Distribution & Transmission Automation Systems	(Climate change OR vulnerability OR risk OR adaptation OR sensitivity OR capacity OR resilience) AND (extreme heat event OR heatwave OR high temperature) AND (overhead cable OR underground cable OR transformer OR switchgear OR protection relay OR control system OR monitoring system OR earthing system)

Energy asset category and key components	Search term
• Substation and network earthing systems	
Energy storage • Battery Storage Systems • Pumped Hydro Storage • Compressed Air Energy Storage • Thermal Energy Storage • Gas Storage Units • Hydrogen Storage Units • Electric Vehicle (EV) lithium-ion batteries	(Climate change OR vulnerability OR risk OR adaptation OR sensitivity OR capacity OR resilience) AND (extreme heat event OR heatwave OR high temperature) AND (energy storage) AND ("battery storage" OR "pumped hydro storage" OR "compressed air energy storage" OR "thermal energy storage" OR "gas storage" OR "hydrogen storage" OR "lithium-ion battery")
Natural gas infrastructure • Gas Transmission and distribution network • Compressor Valves and Regulators • Gas Importation Terminals	(Climate change OR vulnerability OR risk OR adaptation OR sensitivity OR capacity OR resilience) AND (extreme heat event OR heatwave OR high temperature) AND ((gas transmission network OR gas distribution network) OR (compressor valve OR regulator))
Hydrogen • Hydrogen Electrolysers • Hydrogen Pipelines	(Climate change OR vulnerability OR risk OR adaptation OR sensitivity OR capacity OR resilience) AND (extreme heat event OR heatwave OR high temperature) AND (hydrogen) AND ("hydrogen electrolyser" OR "hydrogen transmission unit" OR "hydrogen pipeline")

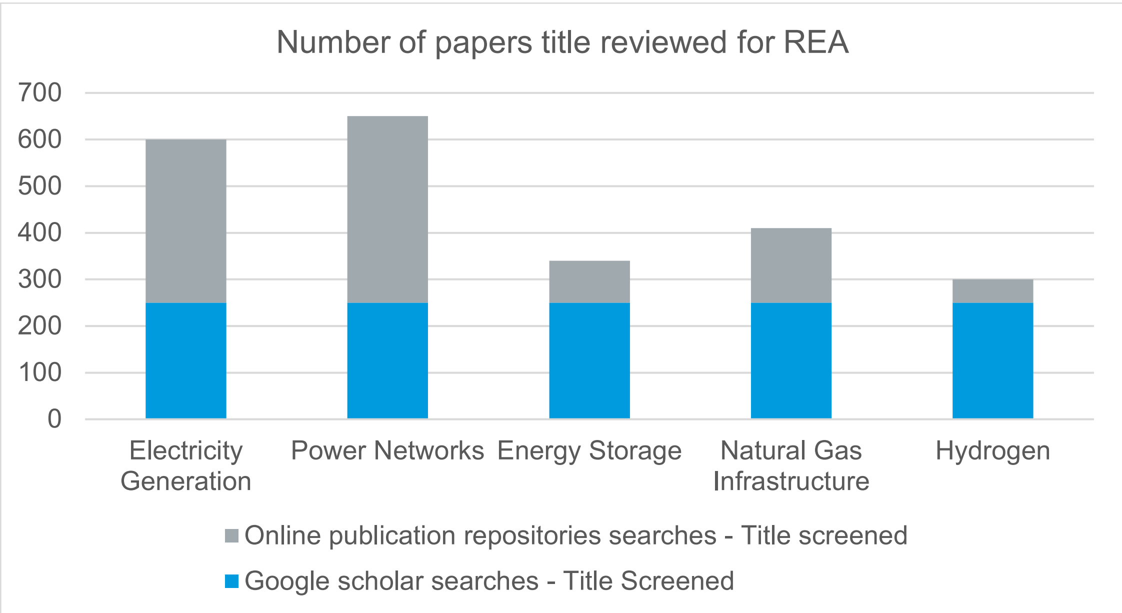
5. A two-step initial screening process was employed to ensure the retrieval of relevant information. First, the top 250 search results, for google scholar searches and the top 20–40 search results for each online publication repositories (for online publication repositories searches, 6–8 databases were searched, and the top 20–40 papers from each database were screened), sorted by relevance, were subjected to title screening. During this process, titles on the search result webpage were reviewed, and any titles lacking relevance to this project were excluded from further consideration.

   Secondly, a dynamic search-term refinement strategy was implemented. If, after screening the top 50 results, a significant decline in relevance was observed, the search term was adjusted to improve the focus of the search. This iterative approach ensured comprehensive coverage of the relevant literature.

6. Each search result/evidence that passed the 'title screening' was added to the evidence extraction template. Table 10 shows the high-level structure of the template. For each piece of evidence that passed title screening, the details indicated in the 'searching for evidence' row was recorded.
7. Abstract screening was performed on each piece of evidence saved in the evidence extraction template. After reading the abstract, evidence that was found to be irrelevant to the aim of this study was excluded from further review.

Figure below presents statistics on the number of papers that were title screened.

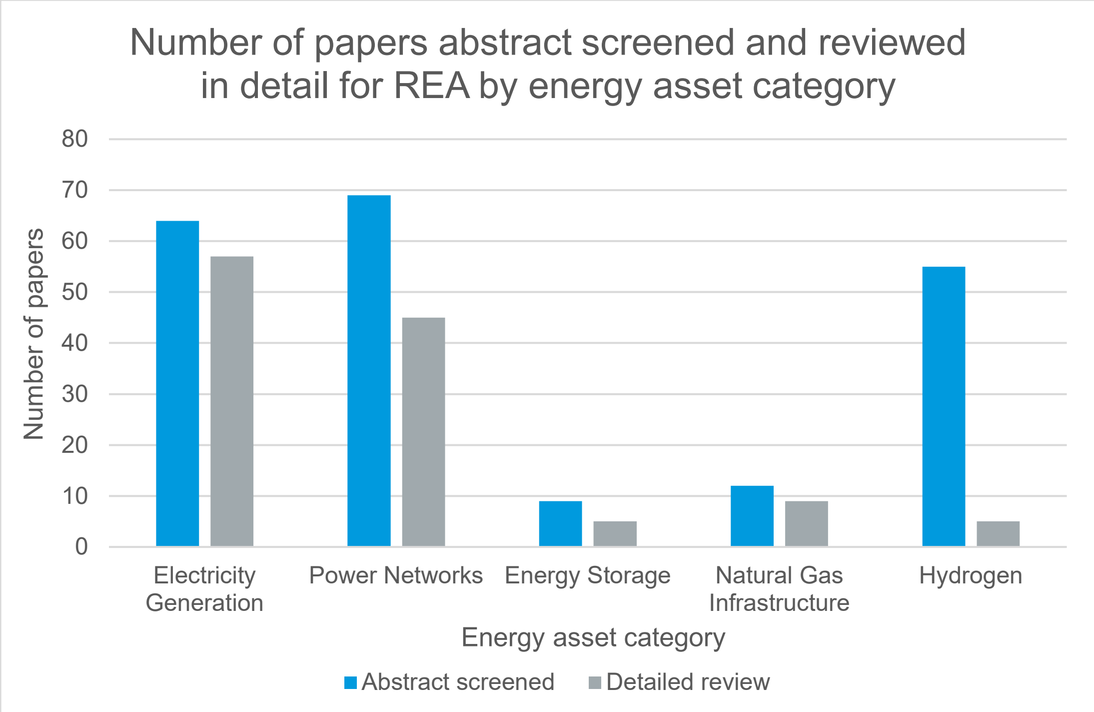
Figure 11 Number of papers title reviewed for REA



A total of 2,300 papers underwent title review, out of which 1,250 papers were from google scholar searches and 1,050 were from online publication repositories searches.

Figure below presents statistics on the number of papers that were abstract screened and number of papers that were reviewed in detail for evidence extraction. 209 papers (out of 2300 that were title screened) passed the title screening stage, and 121 (out of 209 that passed title screening) progressed after the abstract screening.

Figure 12 Number of papers abstract screened and reviewed in detail



Each piece of evidence that was found to be relevant based on its abstract was reviewed in further detail, and all the remaining information indicated in the 'extracting the evidence' row of Table 10 was extracted and recorded into the evidence-extraction template.

Table 10 Evidence extraction database/template

Stage in process/Sub steps	Evidence details that were recorded
Searching for evidence	Author(s), Title, Publication (i.e., journal name), Year, Publisher
Screening the search results	Removed during abstract screening (y/n), Downloaded (y/n)
Extracting the evidence	Literature type, Location, Scale of study, Key messages sensitivity, Key messages adaptive capacity, Key messages exposure, Evidence regarding successful adaptation measures applied to the energy asset category, Key caveats, Evidence on

Stage in process/Sub steps	Evidence details that were recorded
	indirect impacts? (If available), evidence related to each energy type (a column for each)

8. To facilitate review and tracking, each piece of evidence that passed abstract screening was allocated a reference code, which was recorded in the evidence-extraction template.
9. To ensure consistency and quality across the evidence extraction process, in addition to our standard CS-N0W QA process, another team member carried out a blind 10% QA of the evidence screening and extraction.

The information obtained through the REA was used to establish the evidence base for the vulnerability analysis, details of which are provided in the 'Vulnerability analysis' section below.

A.1.1.2 Vulnerability evidence database creation and analysis

This step involved creating an evidence database to assess the vulnerability of energy assets to extreme heat. The process included the following steps:

a. Key messages extracted to the REA evidence template were reviewed, organized, and transferred to the VRA template. The details that were recorded in the VRA database/template are:

- Asset category
- Asset
- Evidence on sensitivity
- Evidence on adaptive capacity
- Exposure
- Evidence on adaptation options

While extracting evidence from REA on the impact of extreme heat on energy assets, the focus was on extracting text that addressed/discussed the below context on ‘sensitivity’, ‘adaptive capacity’, ‘exposure’, and ‘adaptation options’:

Sensitivity:

- Will assets be affected by a change in extreme heat/heatwaves?
- Do assets have a relationship to extreme heat/heatwaves?
- Do assets rely on a certain temperature range/stability of temperatures for vital functions?

Example findings: Higher operating temperatures in transformer lead to faster insulation, and cooling oil degradation, with cellulosic insulation's lifespan halving for every 6°C increase in temperature.

Adaptive capacity:

- Does this sector possess resources that may support its ability to create change?
- What are some resources/initiatives that are existing or planned?

Example findings: Transformers already operating at high loads have limited adaptation capacity, and those with Oil Natural Air Forced cooling systems have better heat adaptation than those with Oil Natural Air Natural systems.

Exposure:

- Which main areas are the assets located in the UK?
- Where are the key activities of the sector occurring?
- What is the interaction between hazard (extreme heat and heatwave) location and the energy assets?

Example findings: Overhead lines have high exposure to extreme heat due to their above-ground installation and direct sunlight exposure. Lines in urban areas experience higher temperatures compared to those in rural areas, partly due to heat island effects.

Adaptation options:

- What are some examples of potential adaptation options i.e. policies, regulations, retrofits etc. that may help to adapt to extreme heat?
- Do these options reduce sensitivity, improve adaptive capacity, or change exposure of the asset to extreme heat?
- Are these options organisational, technical, financial, or ecosystem based?

Example findings: The installation of an inlet air cooling system in gas turbine units to maintain its performance during hot ambient air temperatures, and ii. Introduction of less water-intensive cooling technologies to adapt to water scarcity during extreme heat and heatwaves.

b. The extracted evidence was reviewed by Ricardo's in-house experts to ensure accuracy based on technical and scientific principles.

c. For energy assets for which limited evidence was found in the REA, Ricardo's in-house experts provided input based on their knowledge of the technology and scientific principles to fill those gaps.

A.1.1.3 Stakeholder consultation

To validate the findings from the REA and fill remaining gaps, a stakeholder consultation was carried out. The process began with Stakeholder Identification, where stakeholders were approached via cold emails explaining the purpose of the research and the support required. Following this, survey questionnaire (developed using Alchemer platform) was developed for each energy asset category and was distributed to the stakeholders who had initially agreed to participate in the consultation. The feedback received from the survey responses and subsequent clarification meetings (held on request of stakeholders) was reviewed and incorporated into the findings on vulnerability.

Table 11 provides a list of stakeholders who were contacted and participated.

Table 11 Number of stakeholder's contacted and participated

Energy asset category	Contacted	Participated
Electricity generation	15	• Anonymous Power Generation Company (x3) • Solar Edge Technologies *Total: 4*
Power networks	10	• Anonymous Energy Network (x6) • Electricity Northwest (x2) • National Grid

Energy asset category	Contacted	Participated
		Total: 9
Energy storage	17	• Caldera Heat Batteries Limited • Anonymous Trade Association • Anonymous Power Generation Company • Thermal Storage UK *Total: 4*
Natural gas infrastructure	9	• Anonymous Gas Distribution Network *Total: 1*
Hydrogen	13	• Anonymous Utilities Network (x2) • Anonymous Energy Supplier (x2) *Total: 4*

A.1.1.4 Qualitative rating of vulnerability

This step entailed qualitatively assessing the vulnerability of energy assets to extreme heat using a five-point scale. The process aimed to evaluate the level of vulnerability and facilitate comparisons between assets. The steps involved were as follows:

a) Rating sensitivity and adaptive capacity: Three independent experts individually rated each asset for sensitivity and adaptive capacity on a scale of 1 to 5 (definitions provided below in Table 12 and Table 13) based on findings related to these factors. The final scores for sensitivity and adaptive capacity were determined by averaging these ratings. During the review process, each expert's ratings were kept confidential to avoid bias or influence from others' opinions.

Table 12 Sensitivity definitions for scoring

Sensitivity rating	Definition of ratings	
1	**Low**	**Insensitive to climate:** Asset is not sensitive to changes in heat or temperature
2	**Low-medium**	**Low sensitivity to climate**: Asset is somewhat affected by changes in heat or temperature, operation of the asset is not affected
3	**Medium**	**Climate sensitive:** Asset is affected by changes in heat or temperature, operation of the asset is slightly affected
4	**Medium-high**	**Very climate sensitive:** Asset is affected by changes in heat or temperature, operation of the asset is noticeably affected
5	**High**	**Extremely climate sensitive:** Asset is significantly affected by changes in heat or temperature, operation of the asset is significantly affected

Table 13 Adaptive capacity definitions for scoring

Adaptive capacity rating	Definition of ratings	
1	**Low**	Major challenges to adjust or respond within current extreme temperature/heat wave levels
2	**Low-medium**	Minor challenges to adjust or respond within current extreme temperature/heat wave levels
3	**Medium**	Able to adjust or respond within existing climate limits but major challenges beyond them
4	**Medium-high**	**Able to adjust or respond within existing climate limits but minor challenges beyond them:** Able to adjust or respond within current

Adaptive capacity rating		Definition of ratings
		extreme temperature/heat wave levels, but would experience minor challenges under future climate change (increased intensity/frequency of extreme temperatures exceeded or occurrences of heatwaves)
5	**High**	**Able to adjust or respond regardless of climate:** Able to adjust or respond to extreme temperature/heat wave levels, even if future extreme temperature/heatwaves increase

b) Assigning vulnerability ratings: The final vulnerability rating for each asset was assigned by combining the sensitivity and adaptive capacity scores as per the vulnerability matrix shown in Figure A.5. The vulnerability ratings were sent to Newcastle University for their review, and feedback received was incorporated.

Figure below shows the definition of vulnerability ratings.

Figure 13 Definition of vulnerability ratings.

Vulnerability rating	Definition of ratings
1	Highly resilient
2	Resilient
3	Potentially vulnerable
4	Vulnerable
5	Highly vulnerable

Figure below shows the matrix of vulnerability, interacting ratings of adaptive capacity and sensitivity.

Figure 14 Vulnerability matrix

Adaptive capacity						
	5	1	2	2	3	3
	4	2	2	3	3	4
	3	2	3	3	4	4
	2	3	3	4	4	5
	1	3	4	4	5	5
Vulnerability		1	2	3	4	5
		Sensitivity				

A.1.2 Results

This section presents **asset-specific vulnerabilities to extreme heat and heatwaves**. This includes detailed results from the qualitative rating of sensitivity and adaptive capacity (and therefore vulnerability, based on Figure), followed by a summary of results from the sensitivity and adaptive capacity analysis.

A.1.2.1 Ratings of vulnerability (sensitivity & adaptive capacity)

Table 14 Ratings of asset sensitivity and adaptive capacity, and results vulnerability rating

Asset categories	Asset	Hazard	Sensitivity rating (1-5)	Adaptive capacity rating (1-5)	Vulnerability rating (1-5)
Electricity generation	Gas Power Plants and CCS	Extreme heat	3	4	3
		Heatwaves	3	4	3
	Nuclear Power Plants	Extreme heat	3	4	3
		Heatwaves	3	4	3
	Solar Panels	Extreme heat	3	4	3
		Heatwaves	3	4	3
	Wind Turbines	Extreme heat	2	4	2
		Heatwaves	2	4	2

Asset categories	Asset	Hazard	Sensitivity rating (1-5)	Adaptive capacity rating (1-5)	Vulnerability rating (1-5)
	Hydro	Extreme heat	3	3	3
		Heatwaves	4	3	3
Power networks	Overhead Lines - Transmission, Distribution, and HVDC lines	Extreme heat	4	4	3
		Heatwaves	4	4	3
	Distribution Underground cables	Extreme heat	4	3	4[8]
		Heatwaves	3	3	4[8]
	Transmission & Distribution Transformers	Extreme heat	4	3	4[8]
		Heatwaves	4	3	4[8]
	Service Lines and Connections	Extreme heat	4	3	4
		Heatwaves	4	3	4
	Switchgears, circuit breakers and other protection devices	Extreme heat	4	3	4
		Heatwaves	4	3	4
	Power Electronics, Converters, Filters and Interfaces	Extreme heat	3	3	3
		Heatwaves	3	3	3
	Control, monitoring and Metering Equipment	Extreme heat	3	3	3
		Heatwaves	3	3	3

[8] In the report 'Review of the Climate Resilience of the Net Zero Innovation Portfolio' (R1) developed under the CS-N0W programme, a qualitative vulnerability assessment of net zero technology is presented. The study determined that 'Power Networks' are 'potentially vulnerable' (vulnerability rating of 3). Whereas the study presented in this report (R2) determined that these specific assets within power networks are 'vulnerable' (vulnerability rating of 4). R2 explored vulnerabilities at a more granular level, assessing the vulnerability of 9 specific energy assets within the power network, whereas R1 conducted a higher-level review, assessing the vulnerability of power networks as a single unit. The increased granularity in R2 resulted in a higher vulnerability rating due to the inclusion of 'underground cables' and 'transformers. These assets are more likely to experience long-term thermal stress (caused by rising average ground temperatures and limited flexibility for adjustments) and increased air conditioning demand driven by higher ambient temperatures, respectively.

Asset categories	Asset	Hazard	Sensitivity rating (1-5)	Adaptive capacity rating (1-5)	Vulnerability rating (1-5)
	Distribution & Transmission Automation Systems	Extreme heat	4	4	3
		Heatwaves	3	4	3
	Substation and network earthing systems	Extreme heat	4	4	3
		Heatwaves	4	4	3
Energy storage	Battery Storage Systems	Extreme heat	3	3	3
		Heatwaves	3	3	3
	Pumped Hydro Storage	Extreme heat	3	4	3
		Heatwaves	4	4	3
	Compressed Air Energy Storage	Extreme heat	3	3	3
		Heatwaves	3	3	3
	Thermal Energy Storage	Extreme heat	3	4	3
		Heatwaves	3	3	3
	Gas Storage Units	Extreme heat	3	4	3
		Heatwaves	3	4	3
	Hydrogen Storage Units	Extreme heat	4	4	3
		Heatwaves	3	3	3
	EV lithium-ion batteries	Extreme heat	4	4	3
		Heatwaves	4	4	3
Natural gas infrastructure	Gas Transmission and distribution network	Extreme heat	3	3	2
		Heatwaves	3	3	2
		Extreme heat	3	4	3

Asset categories	Asset	Hazard	Sensitivity rating (1-5)	Adaptive capacity rating (1-5)	Vulnerability rating (1-5)
	Compressor Valves and Regulators	Heatwaves	3	4	3
	Gas Importation Terminals	Extreme heat	3	4	3
		Heatwaves	3	4	3
Hydrogen	Hydrogen Electrolysers	Extreme heat	2	4	2
		Heatwaves	3	4	3
	Hydrogen Pipelines	Extreme heat	3	3	3
		Heatwaves	3	3	3

A.1.2.2 Electricity generation

Nuclear Power Plants

Sensitivity

Nuclear power plants are sensitive to extreme heat as their efficiency is reduced by increased temperatures. The electricity output of nuclear power plants decreases by approximately 0.1-0.5% for every 1°C increase in ambient air temperature [4], [5], [6], [7], [8], [9], [10]. Systems cool less quickly and efficiently during extreme heat; as ambient temperature increases, the temperature of the water used as coolant in a nuclear power plant also increases, making it less effective at condensing steam and absorbing the thermal energy, thereby decreasing the system's operational efficiency. Also, compliance with environmental regulations is reliant on stable temperatures as discharge water temperatures have permitted temperature limits [SC]. Extreme heat may therefore force nuclear plants to reduce operations or shut down, straining the electrical grid during periods of high electricity demand.

Adaptive capacity

Nuclear power plant operators possess the capacity and knowledge to manage temperature extremes; for example, it is known that water-cooled 'once-through' systems are more resilient to temperature fluctuations than recirculating systems [SC]. They are also experienced in considering environmental permit discharge limits, prioritising water use and ecosystem protection during shortages, complying with capacity market contracts to ensure operational security, and engaging with communities during extreme conditions. Nuclear power plant operators also have access to appropriate financial resources for technical interventions to address impacts of extreme heat and for offsetting revenue losses during disruptions caused by extreme conditions. However, some technical interventions are costly; for example, changing the cooling system of an operational plant is not feasible, and cost-benefit considerations vary significantly between plants and systems.

Gas Power Plants and Carbon Capture and Storage (CCS)

Sensitivity

Gas power plants and CCS are sensitive to extreme heat and heatwaves, as the efficiency of gas power plants is diminished by high air temperatures as systems cool less quickly and efficiently. Furthermore, higher air temperatures lead to a reduction in air density, which negatively impacts the cooling efficiency and power output of gas power plants. Gas power plants rely on higher air density and at low temperature to achieve optimal cooling and maintain effective power generation [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23].

The California Energy Commission (CEC) found that the capacity of natural gas combined cycle power plants decreases by 0.3–0.5% for each 1°C increase above a reference temperature of 15°C [24]. Similarly, the power output of natural gas-fired combustion turbines declines by approximately 0.6–0.7% per 1°C increase in air temperature, while combined cycle power plants experience a similar reduction of 0.3–0.5% per 1°C increase[23]. An increase in the average annual temperature of 5°C can reduce the performance of gas turbine thermal power plants by 1.5–2.5% [21], [25].

For example, a typical combined cycle gas turbine (CCGT) with a water-cooled condenser may generate 430 MW of gross power output at a reference temperature of 15°C. If the ambient air temperature reaches 30°C, output may decrease to 410 MW. In comparison, a similar plant with an air-cooled condenser could see a reduction in power output drops further to 370 MW under ambient air temperature of 30°C [SC].

The efficiency of a gas turbine is more affected by air cooling compared to water cooling, with dry cooling systems facing greater losses as air temperatures rise. This difference becomes more in hot temperatures, where ambient air above 40°C severely limits dry cooling efficiency. Many power generation sites would be affected by high temperatures, meaning plant output will also be decreased [SC- Gas Generation Company].

Adaptive Capacity

Gas power plant owners have a good understanding of plant behaviour under extreme heat events and possess the organisational and technical capacity to manage such conditions. Operators are familiar with plant functioning at high temperatures and are prepared with solutions such as circulating cooling and heat-resistant materials. However, challenges persist in addressing water scarcity and maintaining turbine and generator efficiency during extreme conditions. Plant operators are able to allocate emergency funds and purchase insurance to manage financial risks associated with extreme heat, while also investing in advanced cooling systems. Under ecosystem capacity, many gas power plant owners have planted vegetation near operational sites to mitigate heat impacts on infrastructure and enhance efficiency by providing natural heat shielding [Ricardo in-house expertise].

Solar Panels

Sensitivity

Solar power plants are sensitive to extreme heat, which can reduce the efficiency of photovoltaic (PV) cells. As temperatures rise, the materials in PV cells become less effective at converting sunlight into electricity. Solar cell efficiency depends on the temperature of the cells, with a drop of 0.45% for every 1°C rise in temperature above 25°C, especially for certain crystalline silicon technologies [26]. Extreme heat events can also cause physical damage to solar cells and related infrastructure such as cables, joints and connections and degradation of material. For every degree increase in array temperature above 25°C, the efficiency of the panel drops by 0.2–0.5% [12], [14], [24], [25], [26], [27], [28] . For example, a 10 MW solar power plant operates efficiently at 25°C. At 28°C when temperature increases, its efficiency drops by 1.35%, reducing output by 0.135 MW to 9.865 MW; this demonstrates the impact of higher temperatures on power generation. Climate change will affect air temperatures and the occurrence, type, and dissipation of clouds, which in turn will affect electricity generation by PV and concentrating solar power (CSP) plants [15]. It was noted that solar PV systems and inverters become less efficient at higher temperatures, highlighting the sensitivity of solar power plants to extreme heat events [SC- Solar PV].

Adaptive Capacity

Solar power plants can manage extreme heat and heatwaves by adjusting operations on the basis of real-time monitoring and adapting maintenance schedules based on temperature forecasts. Solar panels are built to international standards for higher temperature ranges than those typically seen in the UK, and can operate at cell temperatures up to 85°C and ambient temperatures of 50°C. This design ensures resilience during high-temperature events, though efficiency may still decrease under extreme conditions, although prolonged heatwaves might pose challenges, as the technical capacity of solar panels have some limitations to handle such events. For example, larger plants use cleaning robots to maintain efficiency without significant operational changes. However, adapting to extreme heat requires minimal financial investment due to the simple structure as solar PV systems possess less technically/mechanically complex components. The surrounding ecosystem also helps mitigate heat. Soil, trees, and forests near solar PV plants regulate temperatures, preventing extreme levels and absorbing minor temperature increases.

Wind Turbines

Sensitivity

Wind turbines are resilient to extreme heat as predicted increases in UK temperature are less likely to cause turbine shutdown [27]. However, high ambient temperatures could impact the power production due to decrease in air density. [4], [22]. High ambient temperature could accelerate wear and tear of the components and increase in cooling demand.

Offshore wind farms may face disruptions due to changes in the migration patterns of birds caused by warming climates. If these patterns shift from the assumptions made during the design phase, it could lead to operational challenges or physical damage, such as collisions or altered interactions with turbines [DESNZ]. Onshore components like inverters and other cooling-dependent components also face increased maintenance needs during high temperatures, which can strain the organisation's capacity to manage operations effectively. Heatwaves further increase cooling demands, leading to raise the operational costs, and putting strain on technical and financial capacities. In result, the insufficient cooling systems may also lead to equipment failures or downtime [DESNZ]. These factors highlight the potential sensitivity of wind power systems to heat-related challenges.

Adaptive Capacity

Organisations understand the behaviour of wind turbines in extreme heat and conduct regular monitoring, staff training, and stakeholder engagement to ensure improved efficiency and resilience during high temperatures. Wind turbines have technical capacity to adapt to extreme heat by using heat-resistant materials, high-temperature lubricants, cooling systems, and ensuring appropriate ventilation of turbines. Smart control systems and sensors manage operations and reduce the risk of damage, along with design improvements, such as improved aerodynamics and thermal insulation, make turbines more reliable in high temperatures. In United Kingdom, wind power plants are improving their capacity to manage extreme heat by using advanced forecasting systems and AI-based tools. These help to predict wind speeds and energy output, allowing operators to prepare for extreme heat or low wind conditions. To maintain financial stability, operators are establishing emergency funds and buying specialised insurance to protect against any damage from extreme weather. Environmental measures like planting vegetation near turbines, managing water efficiently, and preventing runoff also help cool the area. As a result, this supports both turbine performance and the local environment during extreme heat.

Hydro-Power

Sensitivity

Hydropower plants are sensitive to high temperatures, as heat affects river flow, evaporation rates, and water levels. Higher temperatures increase evaporation which reduces river runoff and electricity generation capacity. Studies suggest that a 2°C rise in temperature with a 10% decrease in precipitation could reduce river runoff by up to 40% and impacting hydropower generation and showing the link between ambient temperature and hydropower performance [9]. Prolonged periods of extreme heat can create these challenges by further reducing runoff, leading to even greater declines in hydropower generation capacity over time [11], [28], [29], [30], [31], [32].

Adaptive Capacity

Hydropower plants in Great Britain are having ability to operate during extreme heat events. Organisational measures include developing flexible operational plans, training staff to address heat-related challenges, and installing real-time monitoring systems. These measures help ensure efficient operations and resilience during high temperatures by enabling quick responses to changing conditions. Turbines and generators have the technical capacity to operate in high ambient temperatures, the performance declines during extended heatwaves, these systems can still function within a certain temperature range without mechanical failure. During periods of lower river runoff due to temperature increases, hydropower plants can continue generation at a reduced level and operate at a steady power output by using the remaining water volume in the reservoir effectively. Real-time monitoring systems are also crucial for maintaining reliability and optimising performance under extreme conditions. Financial capacity of organisations is supported by establishing emergency funds and investing in heat-resistant technology and cooling systems. Operators secure specialised insurance to protect against losses caused by extreme heat. Also, by diversifying revenue streams, such as incorporating energy storage solutions, helps offset costs associated with heat-related challenges. The surrounding ecosystem also contributes significantly to adaptive capacity. Forests and vegetation near reservoirs and rivers provide shade, lowering water temperatures and improving turbine efficiency. Wetlands and forested catchment areas act as natural shield, retaining water during rains and releasing it gradually during dry periods. This helps stabilise river flows, ensuring consistent water availability and reliable operations during extreme heat.

A.1.2.3 Power Network components

Overhead Lines - Transmission, Distribution, and HVDC lines

Sensitivity

Overhead lines (OHLs) are sensitive to extreme heat because high ambient temperatures impede their ability to effectively dissipate heat from the conductor, reducing their current carrying capabilities. Additionally, conductors expand when heated, which reduces their tensile strength and causes them to sag. Extreme heat could cause the conductor to sag more, exceeding the minimum clearance limit from the ground. [SC - Distribution Network Operator; [23], [33], [34], [35], [36], [37], [38], [39], [40], [41], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], Increasing temperatures may also cause ground drying, which could have an influence on the foundations of the supporting towers [52].

The typical design temperature/maximum conductor temperature for which OHLs are currently being designed in UK is 75°C, with an additional allowance of 5°C to account for climate change. Average thresholds for ambient temperatures are set at 2°C for winter, 9°C for spring and autumn, and 20°C for summer. A 1°C increase in ambient temperature can lead to a capacity reduction ranging from 0.6% to 1.6% [SC - Distribution Network Operator].

Prolonged periods of elevated temperatures can lead to faster loss of tensile strength in the conductor, potentially leading to outages due to excessive sag. Heat waves can push transmission and distribution lines to the limits of their design capacity, especially when combined with increased electricity demand for cooling. This increases the likelihood of widespread blackouts [33], [34], [35], [36], [37], [39], [40], [41], [19], [33], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48].

Adaptive capacity

Network operators have a good understanding of the behaviour of overhead lines (OHL) and how to manage them under extreme heat to avoid service interruptions [Ricardo in-house experts]. The cables and overhead conductors used in UK are designed and manufactured to international standards, enabling them to operate safely within temperature ranges beyond those typically found in the UK [56].

To address the loss of clearance caused by thermal sagging, some Distribution Network Operator (DNO) companies have started installing or have already installed taller poles during pole replacement programs [56]. Any reduction in capacity due to heat is managed as part of

DNOs' business-as-usual (BAU) asset replacement and reinforcement programs [SC – Distribution Network Operator].

For each price review, DNOs and Transmission Operators (TOs) are required to submit detailed plans to the regulator 'Office of Gas and Electricity Markets' (Ofgem), which then determines the amount of revenue that can be recovered from customers. Recently, DNOs have also started factoring in the impact of climate change when estimating the necessary investment and return [SC - Distribution Network Operator]. Ecosystem capacity to adapt to extreme heat is limited or in some cases, may be entirely absent, depending on the local conditions [Ricardo in-house experts]. However, as projected temperatures rise over this century, network operators will need to update their design policies and asset management strategies [SC – Distribution Network Operator].

Distribution Underground Cables

Sensitivity

Underground cables are sensitive to extreme heat because elevated ground temperatures impair their ability to dissipate heat from the conductor, reducing their current-carrying capacity [21], [33], [35], [39], [41], [42], [46], [47], [50], [51], [57], [58], [40], [43]. While less exposed to sunlight than overhead cables, underground cables are still sensitive to extreme heat as it can accelerate corrosion and cause soil shrinkage. This can cause hot spots within the cables and increase tensile forces that can damage the cable [57], [59].

Underground cables are more prone to permanent damage in comparison to overhead lines, as they are likely to experience worse long-term thermal stress, because of increase in average ground temperatures and limited flexibility to adjust, potentially leading to permanent insulation damage. In contrast, while overhead lines may sag when overheated, but they can recover once cooled [SC - Distribution Network Operator]. Prolonged period of elevated temperature could degrade cables faster [SC - Distribution Network Operator].

Paper-insulated lead-covered cables are rated/designed for a maximum temperature of 65°C, Poly Vinyl chloride (PVC) cables for 70°C, and Cross-linked Polyethylene (XLPE) cables for 95°C. The thermal ambient temperatures currently used for assessment/designing in UK are 15°C for summer, 12°C for spring and autumn, and 10°C for winter. A 1°C increase in ambient temperature can result in a capacity reduction of 0.6% to 1.6% [SC - Distribution Network Operator].

Common types of underground cable types and installation methods used in the UK and typical ratings reductions per degree of increase in the average ambient temperature above designed ambient temperature (calculated using CRATER software) is shown in Table 15 below.

Table 15 Commonly used cable types and installation methods the percentage reduction in rating per °C of air temperature change calculated using CRATER

Description	Max °C	Time	Installation	Existing Rating (Amps)	Rating Reduction %/°C Air Temp
LV - 185 Cu Waveform	80	Summer	Direct Lay	339	0.59
LV - 185 AL PILC-STA	80	Summer	Direct Lay	335	0.597
11kV - 185 Al XLPE 1C	90	Summer	Direct Lay	370	0.507
11kV - 185 Al XLPE 1C	90	Summer	Ducted	360	0.521
11kV - 185 Al PICAS 3C	65	Summer	Direct Lay	270	0.787
33kV - 185 Al XLPE 1C	90	Summer	Direct Lay	457	0.492
33kV - 185 Al XLPE 1C	90	Summer	Ducted	430	0.494
33kV - 185 Cu PILC 'H'	65	Summer	Direct Lay	355	0.775
132kV - 630 XLPE 1C	90	Summer	Direct Lay	881	0.511
132kV - 630 XLPE 1C	90	Summer	Ducted	879	0.512
132kV - 630 Cu Lead Sheath	85	Summer	Direct Lay	755	0.579
132kV - 630 Cu Lead Sheath	85	Winter	Direct Lay	827	0.544
400kV - 2000 XLPE 1C	90	Summer	Direct Lay	1,429	0.56
400kV - 2000 XLPE 1C	90	Summer	Ducted	1,448	0.57
400kV - 2000 XLPE 1C	90	Winter	Direct Lay	1,569	0.518
400kV - 2000 Cu Lead Sheath	85	Summer	Direct Lay	1,052	0.986

Adaptive capacity

Although organisations understand the behaviour of underground cables under high temperatures, their capacity to adapt underground cables to extreme heat is limited due to the challenges involved in maintaining/accessing underground cables and the limited visibility of their operating temperature because of limited monitoring used at distribution level [SC - Distribution Network Operator]. In addition, there is low technical capacity to adapt to prolonged period of elevated temperatures. While the thermal mass of soil helps cables adapt to short-term heat, more frequent or prolonged period of elevated temperatures will cause faster degradation and so ecosystem capacity is limited [SC - Distribution Network Operator].

For each price review, DNOs have to submit detailed plans, and Ofgem agrees on the amount of revenue that can be recovered from customers. DNO's have recently started considering the changing climate impact as well for estimating the required investment and return [SC - Distribution Network Operator]. In the last price review, for majority of DNOs Ofgem approved only 90-95% of the proposed investment, which could impact network operators' financial capacity to invest in adaptation measures [Ricardo in-house experts].

Transmission & Distribution Transformers

Sensitivity

Transformers are vulnerable to extreme heat as high temperature impacts their ability to dissipate heat, affecting current carrying capability. Higher operating temperatures leads to faster degradation of insulation and cooling oil [21], [23], [35], [36], [40], [41], [42], [43], [44], [46], [47], [50], [52], [54], [55], [58], [60]. For example, the lifespan of cellulosic insulation halves with every 6°C increase in temperature. This affects their designed life and, in extreme cases, can cause catastrophic failure of the unit [42]. Prolonged periods of high temperatures combined with increased demand for cooling can cause the design limits to be reached faster, further accelerating the degradation [Ricardo in-house experts].

The majority of stakeholders consider distribution transformers to be more vulnerable in comparison to transmission transformers, as 1) most high voltage transformers are run in a redundant mode meaning that they are not operating at full rating, and under these conditions, increases in ambient temperature is not expected to cause operating temperature to rise to the designed hotspot temperature above which significant degradation begins, 2) distribution transformers generally do not have forced cooling systems unlike bigger units [SC - Distribution Network Operator].

In UK, transformers are typically designed for ambient temperatures of up to 40°C. For outdoor locations, the maximum and minimum design ambient temperatures are 40°C and -25°C, respectively, while for indoor locations, they are 40°C and -5°C. In general, 11kV distribution transformers are de-rated by ~1.0%/°C whilst the larger 33kV, 66kV and 132kV transformers that have external cooler banks with fans and pumps are impacted by some 0.7 %/°C [56].

According to BSEN 60076 (British Standard (BS) version of the European Standard (EN) 60076 which provides guidelines for the design, testing, and operation of power transformers), to ensure optimal transformer performance, the external ambient temperature must not exceed 40°C at any time and must not exceed a monthly average of 30°C or a yearly average of 20°C [SC - Distribution Network Operator].

Adaptive capacity

Organisations have limited insight into transformer hotspot temperatures due to the lack of monitoring systems on some transformers. However, they understand available solutions and are required to integrate temperature rise into future network planning, with the necessary resources to manage these challenges [Ricardo in-house experts].

Transformers already operating at high loads have limited technical adaptation capacity, and those with Oil Natural Air Forced (ONAF) cooling systems have better heat adaptive capacity than those with Oil Natural Air Natural systems (ONAN) [SC - Distribution Network Operator].

For each price review, DNOs have to submit detailed plans, and Ofgem agrees on the amount of revenue that can recovered from customers. DNO's have recently started considering the changing climate impact as well for estimating the required investment and return [SC - Distribution Network Operator]. In the last price review, for majority of DNOs Ofgem approved only 90-95% of the proposed investment, which could impact network operators' financial capacity to invest in adaptation measures [Ricardo in-house experts].

The immediate surroundings — such as being installed outside a large building with heavy air conditioning, near a factory, or in the basement of a mall with poor ventilation — can have a significant impact on the transformers operating temperature [SC - Distribution Network Operator].

Service Lines and Connections

Sensitivity

Service lines, similar to underground cables and overhead lines, are sensitive to extreme heat, as elevated ambient temperatures impede heat dissipation, reducing current-carrying capacity. This can degrade insulation in underground lines, create hotspots, and, for overhead lines, elevated temperature can reduce tensile strength and cause excessive sag [Ricardo in-house experts]. While most stakeholders consider service lines similarly sensitive to distribution cables, one stakeholder noted they may be less sensitive due to their shorter length [SC - Distribution Network Operator]. However, service lines are typically less robust, and potentially more sensitive than underground cables, especially older lines [Ricardo in-house experts]. Prolonged high temperatures accelerate degradation and push service lines to their technical limits [Ricardo in-house experts].

Joints and connections are particularly sensitive to extreme heat due to increased stress [52] and loss of tensile strength, which can lead to mechanical failures and reduced efficiency in electrical transfers [34], [61]. Opinion within the sector is split between which is more sensitive, out of cables and joints; some are of the view that joints and connections are more sensitive (citing experiencing 33 kV joint failures during hot summer conditions) and are likely to fail before cables, and some think otherwise. [SC - Distribution Network Operator]. Prolonged exposure to high temperature exacerbates stress on joints and connections, potentially pushing them to their technical and mechanical limits faster [Ricardo in-house experts].

Adaptive capacity

Organisations are required to factor in temperature rise when planning their network and ensure they have the necessary resources to address this. In urban areas, the capacity of organisations is limited due to challenges in maintaining underground service lines, whereas overhead service lines in rural areas face fewer constraints, allowing for easier upkeep [Ricardo in-house experts].

The variability in types, standards, manufacturers, and environments makes it difficult to assess the technical capacity of service lines to adapt to temperature increases [SC – Distribution Network Operator]. While they may handle brief high temperatures, long-term adaptation is limited due to cumulative damage [Ricardo in-house experts]. Similarly, joints and connections can withstand short-term heat but suffer from cumulative stress over time. [Ricardo in-house experts].

For each price review, Distribution Network Operators (DNOs) submit investment plans to Ofgem, which approves the recoverable revenue. Recently, DNOs have started factoring in climate impacts when estimating required investments. However, in the last price review, Ofgem approved only 90-95% of proposed investment, potentially affecting financial capacity [Ricardo in-house experts].

Underground service lines benefit from the insulating effect of surrounding earth, which reduces exposure to extreme heat compared to ambient temperatures [Ricardo in-house experts]

Switchgears, Circuit Breakers, and Other Protection Devices

Sensitivity

Switchgears and protection devices are highly sensitive to extreme heat, as high temperatures accelerate component degradation, impair insulation, and reduce mechanical strength, leading to potential malfunctions and operational difficulties [36], [52]. Their capacity decreases with rising ambient temperatures, with continuous current ratings significantly derating above 40°C [Ricardo in-house experts]. For instance, at 55°C, a 600A device derates to 454A, translating to a 25% reduction in operating capacity [Ricardo in-house experts].

Extended periods of high temperatures can further reduce the capacity of switchgears or cause them to trip, potentially resulting in supply loss or damage. Prolonged period of high temperature could also raise temperature in switch rooms above optimal levels, making them vulnerable to faults [56].

Oil-immersed switches and circuit breakers are typically designed for ambient temperatures of up to 40°C, but fluctuations in temperature and insufficient cooling can exacerbate their sensitivity and affect reliability. While stakeholders generally view the current design temperature (40°C) as suitable for the UK, reliability can be compromised due to failures in telecom and supporting equipment, such as batteries, which may overheat or fail due to poor ventilation, as highlighted by a failure experienced by one Distribution Network Operator [36], [52], [56], [SC - Distribution Network Operator].

Assessing sensitivities is further complicated by the diversity of switchgear types, suppliers, and maintenance standards across the network. Stakeholders find it challenging to determine whether switchgear, circuit breakers, or protection devices are more sensitive without comprehensive testing. However, it is agreed that these assets are more sensitive to extreme heat than electricity generation assets, as heat can not only reduce efficiency and operational capacity but also cause direct mechanical degradation and failure if cooling is insufficient [Ricardo in-house experts; SC - Distribution Network Operator].

Adaptive capacity

Organisations are aware of the impact of high temperatures on switchgears and protection systems, incorporating temperature rise considerations into their planning. Many DNO switch rooms and plant enclosures utilise natural ventilation to maintain optimal operating conditions, with forced ventilation or air conditioning employed when necessary to mitigate heat build-up [56].

The RIIO-ED2 package sets investment levels for DNOs, but recent price reviews have led to Ofgem approving only 90-95% of proposed investment, which may slightly affect financial capacity [Ricardo in-house experts].

In some cases, natural cooling methods, such as trees and water bodies, support outdoor cooling, while indoor assets benefit from buildings with passive ventilation systems [Ricardo in-house experts; SC - Distribution Network Operator]

Power Electronics, Converters, Filters, and Interfaces

Sensitivity

Semiconductor devices, such as power electronics and converters, are highly sensitive to extreme heat, as they perform optimally at lower temperatures. Elevated temperatures can lead to reduced power output and potential damage, with inverter efficiency notably decreasing by 2.5% when ambient temperatures exceed 37°C and degrading significantly beyond 45–50°C [55] [62]. High thermal loads caused by heat and solar irradiation exacerbate power losses in PV inverters, increasing the risk of failures in critical components like diodes and capacitors. Capacitors are vulnerable to high temperatures, which reduce capacitance, raise core temperatures, and negatively impact overall system reliability [63]. Prolonged period of elevated temperature could lead to accelerated degradation and design limits to be reached faster [Ricardo in-house experts].

Inverters achieve peak efficiency (96–96.5%) below 40°C, derating occurs beyond 45-50°C at rates between 2.778% and 5% per degree [64]. All stakeholders recognise the shared sensitivity of power electronics, converters, filters, and interfaces to thermal conditions, emphasising the importance of their location. Whether housed outdoors in a marshalling kiosk or indoors in a relay or telecoms room, the equipment's placement significantly influences its vulnerability and operational reliability [SC - Distribution Network Operator].

Adaptive capacity

Organisations enhance adaptive capacity by conducting preventive maintenance, providing specialised training, and investing in high-temperature infrastructure. Advanced cooling systems, heat-resistant materials, and real-time monitoring are implemented in power electronics, converters, filters, and interfaces to prevent overheating and ensure reliable operation under extreme heat conditions. Companies also prioritise R&D and adhere to regulatory standards to maintain performance and reliability [Ricardo in-house experts].

Financial strategies play a critical role, with budgeting allocated for cooling system upgrades, heat-resistant materials, and regular maintenance to mitigate heat-related wear. Additionally, the broader energy ecosystem supports resilience by leveraging natural cooling methods and ensuring grid stability through industrial coordination [Ricardo in-house experts].

Control, Monitoring and Metering Equipment

Sensitivity

Control, monitoring and metering equipment are sensitive to extreme heat [37], [47] as semiconductors components, such as capacitors and inductors which are basic building block of these devices, rely on stable, low temperatures for optimum performance. High temperatures can affect the heat dissipation and cause thermal expansion, leading to potential failures or inaccurate readings [Ricardo in-house experts]. Prolonged period of elevated temperature could lead to accelerated degradation of components [Ricardo in-house experts].

Stakeholders consider location (whether is it outside in a marshalling kiosk or in a relay or telecoms room in a building) of the equipment, to be a major factor influencing the level of sensitivity [SC – Distribution Network Operator]. Modern electronic equipment is notably sensitive to extreme heat conditions due to their use of complex circuit designs and advanced semiconductor components (which are highly sensitive to temperature change). This can result in circuit malfunctions and, consequently, the failure of the equipment [Ricardo in-house experts]. In addition, the reliability of control, monitoring, and metering equipment can be compromised not only due to issues within the equipment itself but also because of failures in supporting systems, such as telecommunication infrastructure. As, supporting infrastructure often rely heavily on batteries for their operation, and battery performance can degrade under high temperatures, further impacting overall system reliability [SC - Distribution Network Operator].

Adaptive capacity

Organisations conduct staff training, carry out regular calibration checks, preventive maintenance, have established robust emergency protocols, set aside budget for cooling system upgrades, and ensure effective communication channels to enhance resilience of control, monitoring, and metering equipment against heatwaves and extreme temperatures [Ricardo in-house experts]

Where possible, organisations install equipment in shaded locations or in space with adequate ventilation, and follow guidelines as recommended by the manufacturer This ensures technical adaptive capacity to high temperatures [SC - Distribution Network Operator]. However, under sustained or repeated extreme temperature events, degradation will accelerate, increasing the difficulty and cost of repair [Ricardo in-house experts].

Large primary grid substations have climate control systems; however, distribution assets often lack cooling units and are frequently located in constrained spaces, limiting the adaptive capacity of control, monitoring and equipment used in distribution transformer environment [SC – Distribution Network Operator]

Distribution & Transmission Automation Systems (DTAS)

Sensitivity

DTAS are sensitive to extreme heat as high temperatures can degrade the functionality and efficiency of supporting infrastructure (such as control, monitoring, and metering equipment, batteries), which are the basic building block of these systems [54], [SC – Distribution Network Operator].

Extended high temperature can affect the sensors and control devices used within the DTAS systems, which can create data & control issues and increase the potential for cybersecurity breaches and potential cyberattacks. Heatwaves also create challenges in maintaining the equipment, posing a safety risk [Ricardo in-house experts].

Adaptive capacity

Organisations invest in heat-resistant materials, cooling technologies, system upgrades, and advanced monitoring systems to ensure the resilience of DTAS under extreme heat conditions. They leverage predictive analytics, adapt maintenance schedules, train staff to manage assets effectively, and collaborate with meteorological services to optimise responses [Ricardo in-house experts].

DTAS are designed with heat-resistant materials, advanced cooling systems, and thermal sensors to withstand temperature ranges typically observed in the UK. These devices incorporate rugged enclosures, heat sinks, and real-time monitoring systems to maintain stable operation during heatwaves [Ricardo in-house experts].

Substation and Network Earthing Systems

Sensitivity

Earthing systems are sensitive to extreme heat because the effectiveness of earthing systems could be reduced due to an increase in soil resistivity due to soil dryness caused by high temperature [SC—Distribution Network Operator]. Increase in average ground temperature due to extended period of high temperature can significantly impact the effectiveness of earthing systems [Ricardo in-house experts].

In addition, extreme heat can cause conductors, components, and joints to undergo expansion and put excessive stress on the earthing system [34]. This sensitivity, combined with humidity, can accelerate corrosion, reducing earth resistance and the effectiveness of earthing systems [Ricardo in-house experts].

Adaptive capacity

Regular inspections, staff training, budget are set aside for regular maintenance and calibration checks and emergency response plans are conducted for maintaining earthing systems during extreme heat [Ricardo in-house experts]. Generally, earthing systems are designed to cater for a degree of seasonal and regional variations [56], so that may have some technical capacity to adapt to few extreme temperature days [Ricardo in-house experts]. Upgrading large earthing system may require significant investment, so organisations financial capacity might be limited, if extreme temperature impact on earthing system is not already being considered in investments plans [Ricardo in-house experts]

Natural cooling and shade because of being buried in the ground could provide some support in the protection of earthing systems from extreme heat. But in general, without thoughtful intervention, ecosystem has limited capacity to protect earthing systems from extreme high temperatures [Ricardo in-house experts].

A.1.2.4 Energy storage

Battery Energy Storage Systems (BESS)

Sensitivity

Lithium-ion (Li-ion) based Battery Energy Storage Systems (BESS) are sensitive to extreme heat, as they rely on lower, stable operating temperature (15°C to 35°C) for optimal performance [65]. High ambient temperatures can push BESS operating conditions beyond this range and put excessive strain on BESS Heating, Ventilation and Air Conditioning (HVAC) systems, accelerating thermal aging, shortening their lifespan, affecting power and capacity, generating excessive heat that poses safety risks and potentially causing irreversible damage to the batteries. Elevated temperatures also accelerate the degradation rates of all components within Li-ion batteries [59], [66].

Prolonged operation at high temperature causes faster degradation of batteries and increase the potential for thermal runway, which may lead to self-ignition and explosion [66].

Adaptive capacity

BESS owners and developers possess a strong understanding of the technical behaviour of large-scale BESS under high temperatures and the associated challenges [SC - Large scale BESS Developer]. Due to regulatory obligations, they are both motivated and required to integrate temperature considerations into network planning and design [Ricardo in-house experts].

BESS have some technical capacity to adapt to extreme heat, as their HVAC systems are routinely designed to handle ambient temperatures up to 45°C, which are common in some other parts of the world. Therefore, in the UK, even with increasing temperatures, these conditions should remain within the operating envelope of the BESS cooling systems, and hence can maintain the BESS optimal operating temperature [SC - Large-scale BESS Developer]. For LFP (Lithium-ion phosphate) BESS, as per UL9540A (the standard for test method for evaluating thermal runaway fire Propagation in BESS), the temperature thresholds for thermal runaway range from 150°C to 200°C, meaning BESS should not be affected by minor increases in ambient temperature [SC - Large-scale BESS Developer]. Continuous exposure to high temperatures can overwhelm BESS cooling systems, which could cause insufficient heat dissipation and lead to thermal runaway and explosions [66].

Manufacturers, owners, and operators of BESS have the financial resources needed to implement necessary measures to adapt to the effects of extreme heat on their assets. They invest in regular maintenance and infrastructure improvements, budgeting for emergency repairs and operational adjustments to ensure resilience against extreme heat. Where possible, organisations arrange for natural cooling through passive ventilation using vegetation and water sources [Ricardo in-house experts]

Pumped Hydro-Storage

Sensitivity

Pumped hydro storage systems are sensitive to extreme heat as they rely on stable temperatures for component efficiency and water retention. High temperatures reduce efficiency and increase evaporation which may lower the system’s operational capacity [Ricardo in-house experts]. During heatwaves, the sensitivity of pumped hydro storage systems is same as experienced during extreme heat but over a prolonged period. The long time continued high temperatures exacerbate reservoir evaporation which can reduce water availability and put additional stress on mechanical components due to high operating temperatures, which potentially lowering the overall system performance [Ricardo in-house experts]. This could impact its ability to store and release water effectively reducing its efficiency during peak demand periods.

Adaptive Capacity

Organisations are adapting and taking steps to ensure resilience through regular maintenance and thermal management practices by maintaining the performance of pumps and generators during heatwaves and it helps in reduce evaporation and supports consistent operational efficiency. Pumped storage systems are now employed with advanced cooling technologies to minimise heat-related impacts. Plant owners are allocating funds for equipment maintenance and reservoir management and investing in infrastructure improvements and budgeting for emergency repairs and operational adjustments to ensure reliable operations during heatwave conditions. Ecosystem capacity to adapt to extreme heatwaves may be limited in some locations and sufficient in others because it largely depending on the local environment where the hydro power plant is situated. The local environment can have a significant impact on water levels and flow rates [Ricardo in-house experts].

Compressed Air Energy Storage

Sensitivity

Compressed Air Energy Storage systems (CAES) are sensitive to extreme heat because the efficiency of air compression, cooling, and turbine performance relies on lower temperatures. A rise in temperature increases the energy consumption for compression, reduces cooling efficiency and accelerates component wear [Ricardo in-house experts]. For example, every increase in 1°C (1.8°F) can increase energy consumption for air compression in CAES systems by approximately 1-2% and increase in this temperature puts additional strain on cooling systems and potentially reducing their efficiency by 0.5-1% per degree Celsius. The long period extreme heat can increase the wear and tear on mechanical components by 1-

1.5% per degree Celsius and in result it can degrade the insulation materials and increase the maintenance intervals and costs. [Ricardo in-house experts].

Adaptive Capacity

In extreme heat, organisations manage Compressed Air Energy Storage (CAES) by deploying skilled teams to ensure effective work in reducing risk of failure, using emergency protocols, and closely monitoring systems to maintain efficiency [Ricardo in-house experts]. Modern CAES systems use intercoolers and aftercoolers to regulate the temperature of the compressed air, thus plants have some additional capacity to adapt to high temperatures, but the thermal management systems may struggle to maintain optimal air temperatures during prolonged heat exposure [Ricardo in-house experts]. Organisations invest in regular maintenance and infrastructure improvements, budgeting for emergency repairs and operational adjustments to ensure operation against extreme heat [Ricardo in-house experts]. In CAES systems, surface equipment such as turbines are often located in remote and rural areas, meaning they may benefit from some natural cooling provided by surrounding vegetation [Ricardo in-house experts]. In response to heatwaves, organisations use predictive analytics to prepare and adjust operations and maintenance schedules for heat-related challenges. Plant owners also coordinate with meteorological services that helps optimise responses and maintain system reliability [Ricardo in-house experts].

Thermal Energy Storage

Sensitivity

Thermal storage units are generally sensitive to temperature changes, as their operation relies on the temperature difference (ΔT) between the ambient air and the storage unit [SC - Trade association for modern thermal storage].

In prolonged period of high temperature (above 40°C) for several days, the units can experience prolonged stress which can cause cooling systems to become less effective, leading to potential efficiency drops of up to 30%. The cooling systems might not be sufficient to prevent overheating, leading to reduced thermal storage efficiency and possible damage to components. During prolonged heatwaves, unwanted heat gains in thermal storage systems can increase by up to 30% due to a larger ΔT. Hot storage systems (Stores heat energy for later use), operating at 400–1000°C, are less affected by these changes due to their high operating temperatures and robust insulation , which typically provide a ΔT of 40°C. Additionally, higher ambient temperatures slightly reduce the ΔT for hot storage systems, improving their efficiency marginally. However, ancillary equipment such as offloading pumps is more vulnerable to extreme heat, requiring optimal operating temperatures of 40–50°C [SC - Trade association for modern thermal storage].

In contrast, cooling storage (Stores cold energy for later use) units, that typically operate -20°C to 15°C [Ricardo in-house experts], are much more sensitive during heatwaves, with the ΔT potentially doubling [SC - Trade association for modern thermal storage]. Prolonged exposure to ambient temperatures above 40°C places significant stress on thermal storage units, reducing cooling efficiency by up to 30% and increasing the risk of component damage. If temperatures exceed 50°C, there is a greater likelihood of operational failure, as the cooling and insulation systems may not be designed to cope with sustained extreme heat [Ricardo in-house experts].

Adaptive Capacity

Organisations existing expertise in thermal management and design requirements, adaptive leadership, and collaboration with stakeholders allows these organisations to adapt to impacts and maintain operational effectiveness during extreme heat events. Organisations set aside a budget for emergency repairs and operational adjustments to ensure resilience against extreme heat [Ricardo in-house experts]. But these capabilities may not be sufficient during a heat wave due to limited awareness, availability, and provision of information from regulators on specific regulations around extreme heat, for e.g., in city guides that are one of the references currently manufacturers use while designing thermal energy storage systems [SC - Trade association for modern thermal storage].

The technical adaptive capacity of thermal energy storage systems lies in their insulation, which is generally designed for efficiency. And, insulation levels are often capped based on cost-effectiveness, with no specific regulations and consideration for extreme temperatures. So, technical capacity and financial capacity to adapt to extreme heat may be limited [SC - Trade Association for Modern Thermal Storage].

Where possible, organisations arrange for natural cooling through passive cooling using vegetation and water sources [Ricardo in-house experts], but ecosystem capacity is limited as most of the ancillary equipment is located in enclosed metal species. These structures heat up quickly and retain heat, causing indoor temperatures to rise significantly [SC - Trade Association for Modern Thermal Storage].

Gas Storage Units

Sensitivity

Gas energy storage units are sensitive to extreme heat as they rely on stable temperatures to maintain gas pressure and tank integrity. High temperatures cause gas expansion which increases pressure and stresses cooling systems [Ricardo in-house experts]. During heatwaves and prolonged high temperatures worsen these sensitivities by placing more strain on storage units and cooling systems. Extended heat increases the risk of long-term damage and reduced efficiency, making effective cooling and monitoring essential [Ricardo in-house experts].

Adaptive Capacity

Organisations managing gas storage units have already started taking steps to enhance their capacity to adapt to extreme heat by using monitoring systems that have been upgraded, staff are regularly trained to handle heat-related challenges, and flexible operational procedures are in place to ensure safe and efficient operations during prolonged heatwaves [Ricardo in-house experts]. Real-time monitoring of temperature and pressure is already in place, enabling timely adjustments to maintain operational safety with ongoing system modifications and technological innovations are continuously enhancing the resilience of these units to withstand prolonged heat exposure [Ricardo in-house experts]. Organisations using financial strategies to adapt gas storage systems to heatwaves by doing regular cost-benefit analyses and contingency funds are in place that allowing organisations to efficiently manage the financial resources required for necessary adaptation [Ricardo in-house experts]. Natural cooling systems such as wetlands and green roofs, are already being utilised by some organisations to reduce heat stress on gas storage units. Existing efforts to maintain and enhance surrounding ecosystems help buffer the effects of extreme heat, and these ecosystem-based strategies provide ongoing protection for both the infrastructure and the environment [Ricardo in-house experts].

Hydrogen Storage Units

Sensitivity

Hydrogen storage units are sensitive to heatwaves and high temperatures given that storage capacity and production efficiency rely on temperature conditions within a range. Overground storage is particularly affected by heat and would necessitates more cooling to maintain plant operations [Ricardo in-house experts]. Hydrogen storage units are designed with environmental hazards, including extreme heat, in mind. This inherent adaptive capacity is embedded in the planning and design stages, ensuring that the materials and systems used are resilient [Ricardo in-house experts].

Adaptive Capacity

Organisations managing hydrogen storage units should have robust operational procedures and employ skilled personnel to effectively handle extreme heat. Ongoing staff training programs should be in place, stringent safety protocols followed, and emergency response plans regularly updated to adapt to prolonged high temperatures. [Ricardo in-house experts].

Hydrogen storage units are designed with environmental hazards, including extreme heat, in mind. This inherent adaptive capacity is embedded in the planning and design stages, ensuring that the materials and systems used are resilient [Ricardo in-house experts].

Organisations allocate financial resources to maintain and upgrade hydrogen storage infrastructure to withstand extreme heat. Contingency funds should exist, and the cost-effectiveness of new technologies regularly evaluated to ensure the continued resilience of these storage systems under heat stress [Ricardo in-house experts].

Existing natural ecosystems around storage sites are integrated to provide additional cooling benefits, helping reduce the overall thermal load on storage units. Organisations should actively support green infrastructure and sustainable land use practices, which enhances the resilience of storage units to extreme heat while protecting the surrounding environment [Ricardo in-house experts].

EV Lithium-ion Batteries

Sensitivity

EV lithium-ion batteries (LiBs) are sensitive to extreme heat as they rely on lower, stable operating temperature (15°C to 35°C) for optimal performance [66], [67]. High ambient temperatures can push BESS operating conditions beyond this range. High temperatures increase internal resistance, reduce capacity, and may trigger thermal runaway [66], [67]. LiBs charge more slowly in the heat, lengthening vehicle recharge times. Under hotter temperatures, the battery's thermal management system works harder to cool battery temperatures to prevent overheating. This consumes energy and thus depletes range, even when the vehicle is parked [67], [68].

Adaptive capacity

Organisations managing EV LiBs have a strong understanding of how high temperatures affect these systems and are obligated to consider temperature impacts in their planning and design processes. They are both motivated and equipped with the necessary resources to respond effectively to the challenges posed by rising temperatures, ensuring the safety and reliability of their networks [Ricardo in-house experts].

EVs are generally equipped with HVAC systems to maintain optimal temperatures for batteries, that can enable them to adapt to intermittent extreme heat. However, prolonged period of high temperature can overwhelm EVs cooling systems, which could lead to inadequate heat dissipation, and ultimately thermal runaway[66]. Thus, while LiBs can handle intermittent exposure to extreme heat, prolonged exposure and operation under extreme heat high temperature are expected to pose a significant challenge to its optimum and safe operation [Ricardo in-house experts].

Manufacturers of EV LiBs possess the financial resources needed to implement adaptation to manage extreme heat. This financial capacity supports ongoing investments in technology upgrades and safety measures to enhance the resilience of LiBs under high-temperature conditions [Ricardo in-house experts].

A.1.2.5 Natural gas infrastructure

Gas Transmission and Distribution (T&D) Network

Sensitivity

Gas utility operators view gas transmission and distribution network in UK as resilient to extreme heat, as gas pipelines in UK are currently designed for ambient temperatures between -30°C and 60°C and operate at nearly 30% of their Specified Minimum Yield Strength (the amount of stress applied to steel before it begins to deform permanently) or below, and therefore are currently operating well within the safety factors, unless associated with specific defects or damage [52], [61], [69], [SC - Gas Utility]. Though, extended period of high temperature could have a minor impact but most vulnerable assets are considered to be the supporting IT equipment and instrumentation (stakeholder - Gas Utility - mentioned experiencing this during the heatwave of 2022) which may need to be housed or supported by cooling (air conditioning) to avoid any overheating and resulting failure [52], [52], [61], [69], [70]. There is an indirect risk to gas pipes, joint and connections due to soil subsidence caused by dry ground condition because of extreme heat [52], [71].

Adaptive capacity

Technical adaptive capacity exists as these assets are manufactured to international standards, meaning they are designed to operate at and cope with higher temperatures than those expected to occur in the UK [52], [61], [69], [70], [71] [SC - Gas Utility]. Therefore, currently, no specific consideration is given to forecasted extreme temperatures in investment plans submitted to Ofgem [SC - Gas Utility]. Adaptive capacity to adapt to indirect risk to joints, connections and pipe from ground movement or subsidence caused by soil dryness is limited especially for older less ductile iron gas mains pipes. Organisations are addressing this by conducting pipeline walking surveys to identify areas prone to ground subsidence and by introducing less vulnerable polyethylene pipe [71].

These assets are mostly underground, protected by soil layers, meaning ecosystem capacity exists. Rural areas offer additional protection/capacity to adapt due to vegetation. [Ricardo in-house experts]

Compressor Valves and Regulators

Sensitivity

Compressor valves and regulators are sensitive to extreme heat, as extended period of high temperature can cause the supporting IT equipment and instrumentation to malfunction [52], [61]. High temperature can also impact the capacity of the compressor to move the gas, as the turbine that drives the compressor produces less power due to decreased air density at high temperature[61], [72], [73] . Additionally, compressors require more power to maintain output in high temperatures, which can affect the flow rate of the gas and accelerate wear and tear on valves and regulators [72], [74], [Ricardo in-house experts].

Adaptive capacity

Organisations carry out review of maintenance regimes and operational procedures to account for increasing temperatures [Ricardo in-house experts]. Technical adaptive capacity exists as these assets are manufactured to international standards, meaning they are designed to operate at and cope with higher temperatures than those expected to occur in the UK [52]. Capacity to adapt under extended period of high temperature can be impacted because of impact on supporting IT equipment and instrumentation [52].

Financial capacity exists, as finance is not expected to be an issue for this asset [Ricardo in-house experts]. Some ecosystem capacity exist as above-ground assets benefit from natural elements like trees and water bodies for cooling. Underground assets are protected by soil and vegetation [Ricardo in-house experts].

Gas Importation Terminals

Sensitivity

Gas importation terminals are sensitive to extreme heat because the Natural Gas arrives in a liquid state (-160°C) and is converted to gas using vaporizers. Higher ambient temperatures slightly improve the efficiency of this process as less additional heat is needed, but at the same time this is negated by the increased consumption for cooling. Increased ambient temperatures can lead to higher heat ingress, increasing the boil-off gas rate, which can cause safety issues and reduced storage capacity due to increase in pressure. At high ambient temperatures, the cooling system may not be able to perform optimally and provide sufficient cooling for re-liquefying the boil-off gas, minimising heat ingress, and maintaining the cryogenic temperature for gas storage. Prolonged period of high temperatures can cause thermal expansion, stressing equipment and potentially affecting the accuracy of flow meters, which are typically specified to operate in ambient temperature of up to 40°C [Ricardo in-house experts].

Adaptive capacity

Organisations carry out review of maintenance regimes and operational procedures to account for increasing temperatures [Ricardo in-house experts]. Technical adaptive capacity exists as these assets are manufactured to international standards, meaning they are designed to operate at and cope with higher temperatures than those expected to occur in the UK [52].

Financial capacity exists, as finance is not expected to be an issue for this asset. [Ricardo in-house experts]. Some ecosystem capacity exists as this asset benefits from natural cooling from wind and from sea water evaporation [Ricardo in-house experts].

A.1.2.6 Hydrogen

Hydrogen Electrolysers

Sensitivity

Hydrogen electrolysers are resilient to extreme heat as the materials of construction in modern electrolysers are built to handle extreme heat levels and their cooling systems exist with controls and are robust for 5~40°C [75], [76], [77]. Higher temperatures than normal operating temperatures (27-29°C) marginally decrease power consumption for electrolysis, although this increases the load on the cooling systems. Compressing hotter gas for onward transmission requires more energy and increases the cooling demands for compressors. Site selection for hydrogen plants take into consideration the availability of water for production and cooling, which can help manage extreme heat occurrences.

However, these devices remain potentially vulnerable to heatwaves, as prolonged periods of high temperature (above 40°C) can cause prolonged stress on cooling systems, leading to reduced efficiency, leading to overheating, and potentially damaging internal component. The thermal cycling, characterised by rapid fluctuations between high and normal operating temperatures, can induce material fatigue in components, increasing the risk of failures and reducing the expected lifespan of the electrolyser and cooling systems [SC - Project Developer].

Adaptive Capacity

Organisations are implementing robust safety cultures by prioritising the use of advanced electrolyser control systems. Regular operation and maintenance regimes ensure the system's optimal condition to withstand heat variations. Furthermore, organisations actively monitor weather warnings to predict periods of increased heat, allowing for proactive preparation and appropriate responses. [Ricardo in-house experts]

Electrolyser control and cooling systems are equipped with alerts for temperatures outside of the operating range, enabling timely interventions. Modern electrolysers are constructed with materials designed to withstand extreme heat levels. While the long-term effects of prolonged heat exposure are still under investigation, the successful operation of electrolysers in hot climates like Saudi Arabia suggests no immediate evidence of significant equipment damage due to extended heat exposure. [Ricardo in-house experts]

Hydrogen Pipelines

Sensitivity

The seals connecting hydrogen pipelines are potentially sensitive to extreme heat while pipelines are less vulnerable as they are buried below ground.

Adaptive Capacity

Regular operation and maintenance regimes ensure the system is in optimal condition to withstand heat variations. Organisations are implementing regular auditing of pipelines to safe check for leaks/cracks [Ricardo in-house experts]. Long term weather prediction / climate change modelling can help with predicting weather events. [SC - Project Developer].

Hydrogen pipelines have technical capacity to extreme heat, as pressure and temperature probes are fitted along pipeline for continuous monitoring. Pipelines already utilise robust and tested materials and construction methods to withstand heat fluctuations. Pipelines are set at a depth that results in minimal effect from surface temperatures. Anticorrosive coatings added to pipes to increase robusticity to heat

Currently, material like PE80 [9] & PE100 [10] are widely used in the UK for gas distribution networks. However, their suitability for high-temperature hydrogen transport may be limited.

Hydrogen pipeline materials will likely encompass a wider range of options, including both plastic and metal pipelines, selected based on factors such as pressure, size, and flow rate. A key difference for hydrogen transport is the potential need to operate at higher pressures or utilize larger diameter pipes to achieve the same energy density as natural gas. This implies that hydrogen pipelines may generally require larger infrastructure compared to equivalent natural gas pipelines." [Ricardo in-house experts]

The well-established UK gas networks are equipped to handle emergency scenarios effectively, allowing for the quick stopping and re-routing of gas flow to maintain supply while isolating networks for non-routine operations. Robust policies and procedures ensure that the appropriate instructions, capabilities, and training requirements are in place for personnel mobilisation during emergencies [SC - Project Developer].

Organisations have financial reserves in order to replace/repair potentially damaged equipment as well as to respond to increased temperature events [Ricardo in-house experts].

Extensive permitting and planning is required for establishing a pipeline route that is the least impactful from an anthropogenic standpoint [Ricardo in-house experts].

Appendix 2 – Exposure Assessment

A.2.1 Methodology

This section presents the methodology used to assess the exposure of energy assets to extreme heat. It then describes the uncertainties associated with the approach taken.

[9] PE 80 is a medium-density polyethylene with a higher strength than standard polyethylene. It has been used for natural gas pipelines for many years.

[10] PE 100 is a high-density polyethylene with even greater strength than PE80. It is also commonly used in natural gas pipelines

A.2.1.1 Projections of extreme heat

To conduct the assessment of exposure, air temperature data was collected and mapped to present the spatial distribution of extreme heat across the UK.

Data and bias correction: Projections of maximum air temperature, measured in degrees Celsius, were used to present the potential future exposure of the UK to extreme heat. The projections, from UKCP18 (UK Climate Projections 2018), are at a daily time interval, at a spatial resolution of 12km², meaning the exposure information is shown on a 12km² grid across the UK. The dataset contains daily projections for every 12km² grid of the UK for every year of the 21st Century.

The maximum air temperature data used in the exposure and impact analysis is bias corrected. 12km² is the highest resolution available for the bias-corrected version of the dataset. Bias correction was conducted to align the projections with historical trends in UK temperatures and therefore project future extreme heat more realistically, as advised by the CCC.

The data was bias corrected to ERA5 and was conducted by colleagues at the University of Bristol based on an evaluation of UKCP18 (Kennedy-Asser et al., 2021 and Kennedy-Asser et al., 2022). ERA5 is the 5th generation of reanalysis conducted by the European Centre for Medium-Range Weather Forecasts (ECMWF). Reanalysis is an alternative to historical observations, as it combines climate model outputs with historical observations to generate a dataset of past climate conditions. ERA5 was used as it contains multiple climate variables at appropriate time frequency, such as daily humidity, that the Met Office observations (HadUK-Grid) does not. However, ERA5 produces lower maximum temperatures than HadUK-Grid observations, and therefore bias correcting to ERA5 is a limitation to this study, as it leads to the most extreme projected temperatures being muted. As a result, the findings of this study may not include the most extreme potential outcomes in projected maximum air temperatures and therefore extreme heat.

Global warming levels and ensemble member selection: The maximum air temperature projections are generated according to multiple different future climate scenarios, known as Global Warming Levels (GWLs). GWLs represent potential increases in the global average air temperature, since the preindustrial period. Along the trajectory of the Representative

Concentration Pathway (RCP) 8.5 scenario, for the period of 1980-2080, data can be extracted that represents the projected outcomes at various GWLs. This is useful as climate model years do not necessarily match what would be expected to happen in real-world years e.g. a climate model might take until 2030 to reach 1.5°C of warming even though the world is already experiencing these temperatures. 1.5°C, 2°C and 2.5°C GWLs have been used in this analysis, which were agreed in discussion with DESNZ and the CCC. These GWLs represent scenarios in which average global temperatures are kept below a 1.5°C, 2°C and 2.5°C increase above pre-industrial levels. These possible future outcomes are dependent on the success of current global efforts to reduce greenhouse gas emissions and mitigate climate change (The CCC, 2020).

An ensemble member selection process was undertaken to identify the members to use within the analysis. Using the UKCP18 maximum air temperature data, there are 12 ensemble members available that provide projections. Each ensemble member simulates the climate slightly differently due to differing initial conditions and the influence of natural climate variability, meaning they each project that the 1.5°C, 2°C and 2.5°C GWLs will be reached at different years.

The full range of maximum UK temperatures projected by the ensemble members were of interest. To present the spread of outcomes, and therefore the uncertainty, between the ensemble members, the members with the minimum, median and maximum T_{max} outputs for the were identified (T_{max} is defined in point 2 below). These were determined by taking the following steps:

1. From the dataset, the maximum air temperature in each grid cell was identified per year, and then averaged across the UK, for each member. This was calculated for the 20-year period spanning the point at which the GWL is expected to be reached per member. Table 16 to Table 18 show the projected data for GWLs 1.5°C to 2.5°C, respectively, showing the maximum air temperatures projected for each year within the 20-year period that spans each GWL being reached, per ensemble member.

Table 16 Maximum air temperatures projected by each ensemble member (averaged across the UK) for the 20-years that span **GWL 1.5°C**

Climate services for a net-zero resilient world

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2003							19.5					
2004							19.9					
2005		19.6					17.7				17.6	
2006		19.3			18.3		20.2		19.8		18.2	
2007		19.3		18.0	17.8	20.9	17.8		20.5		18.3	19.2
2008	18.0	18.4	19.5	18.2	19.5	19.5	18.0		18.0		16.9	18.6
2009	19.2	18.2	18.3	20.4	19.6	17.4	19.9	18.8	17.8		19.9	20.5
2010	19.2	18.8	19.7	20.0	18.4	17.3	20.1	17.1	17.6		19.1	19.8
2011	17.8	19.1	19.0	18.7	17.5	18.8	19.1	18.3	18.4		18.3	19.7
2012	18.6	21.4	18.9	20.4	19.1	17.9	19.4	18.6	20.2	18.3	19.3	19.8
2013	19.5	19.1	18.1	18.5	18.6	18.7	17.6	18.9	18.5	17.8	18.7	18.4
2014	17.9	19.6	18.7	18.1	20.5	19.4	18.3	19.2	19.3	17.8	21.3	17.3
2015	17.8	18.5	18.1	18.7	20.9	19.6	19.8	18.5	19.2	19.8	19.8	19.2
2016	17.5	19.1	20.9	18.2	19.7	19.9	21.1	19.2	18.9	18.8	17.9	19.0
2017	19.6	19.0	20.0	19.2	18.6	19.1	19.1	18.9	19.7	17.9	18.7	19.5
2018	20.0	19.4	21.3	20.4	19.6	19.3	18.2	19.4	21.2	21.4	19.7	18.7
2019	21.3	18.5	18.1	20.7	18.4	20.0	18.6	19.8	19.3	17.9	21.2	19.0
2020	21.1	18.9	18.8	19.5	19.6	21.4	19.9	18.2	21.6	20.0	21.2	18.5
2021	18.8	18.7	20.3	19.6	19.4	20.0	18.6	19.4	18.6	17.8	21.2	19.9
2022	19.2	17.9	22.0	20.5	21.7	20.2	19.3	19.5	19.8	19.4	20.0	20.2
2023	21.4	19.1	20.6	21.4	20.7	19.6		19.7	21.2	20.0	19.8	21.3
2024	18.0	18.9	18.5	20.8	18.8	20.1		20.4	18.9	19.2	19.4	19.1
2025	22.0		19.1	19.9	20.1	22.1		19.8	18.1	19.8		19.7
2026	20.4		18.9	22.5		20.8		18.0		18.0		19.1
2027	19.9		17.9					19.4		20.1		
2028								20.7		17.8		

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2029										19.1		
2030										19.1		
2031										18.9		

Table 17 Maximum air temperatures projected by each ensemble member (averaged across the UK) for the 20-years that span **GWL 2°C**

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2015		18.5										
2016		19.1					21.1					
2017		19.0		19.2			19.1		19.7		18.7	
2018	20.0	19.4		20.4			18.2		21.2		19.7	
2019	21.3	18.5		20.7	18.4		18.6		19.3		21.2	
2020	21.1	18.9	18.8	19.5	19.6	21.4	19.9	18.2	21.6		21.2	18.5
2021	18.8	18.7	20.3	19.6	19.4	20.0	18.6	19.4	18.6		21.2	19.9
2022	19.2	17.9	22.0	20.5	21.7	20.2	19.3	19.5	19.8		20.0	20.2
2023	21.4	19.1	20.6	21.4	20.7	19.6	17.8	19.7	21.2	20.0	19.8	21.3
2024	18.0	18.9	18.5	20.8	18.8	20.1	18.3	20.4	18.9	19.2	19.4	19.1
2025	22.0	19.1	19.1	19.9	20.1	22.1	20.1	19.8	18.1	19.8	19.9	19.7
2026	20.4	20.0	18.9	22.5	19.8	20.8	19.6	18.0	19.4	18.0	19.4	19.1
2027	19.9	19.8	17.9	20.1	19.0	19.2	20.2	19.4	18.9	20.1	21.8	19.5
2028	20.7	19.9	19.3	18.5	22.7	18.5	19.6	20.7	21.0	17.8	20.1	17.3
2029	19.1	20.4	20.4	20.4	19.7	20.6	17.9	19.0	20.0	19.1	19.4	19.8
2030	20.3	20.1	21.3	21.4	19.3	19.6	18.5	19.2	19.9	19.1	20.1	20.8
2031	19.3	20.0	18.7	19.5	19.3	19.0	19.2	19.8	20.0	18.9	21.0	20.6
2032	23.3	19.3	20.3	20.1	19.7	20.3	20.0	20.8	20.8	18.3	19.9	19.4
2033	21.0	19.9	19.6	20.9	20.5	21.3	21.4	19.1	19.5	21.0	21.1	20.2

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2034	21.7	20.2	19.3	19.3	20.7	19.7	18.5	19.2	19.7	19.9	22.9	19.2
2035	19.8		18.6	20.6	20.3	19.8	20.2	20.5	19.7	17.6	20.4	19.8
2036	19.3		20.0	19.6	19.3	20.7		20.4	19.6	19.2	23.2	18.0
2037	20.0		20.8		20.4	19.4		20.2		18.9		17.8
2038			20.2		18.8	22.0		21.2		21.7		20.7
2039			19.9			21.2		20.4		21.7		18.4
2040										20.2		
2041										19.3		
2042										20.6		

Table 18 Maximum air temperatures projected by each ensemble member (averaged across the UK) for the 20-years that span **GWL 2.5°C**

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2025		19.1					20.1					
2026		20.0					19.6					
2027		19.8		20.1			20.2		18.9		21.8	
2028		19.9		18.5			19.6		21.0		20.1	
2029	19.1	20.4		20.4			17.9		20.0		19.4	
2030	20.3	20.1		21.4	19.3		18.5	19.2	19.9		20.1	
2031	19.3	20.0	18.7	19.5	19.3	19.0	19.2	19.8	20.0		21.0	
2032	23.3	19.3	20.3	20.1	19.7	20.3	20.0	20.8	20.8	18.3	19.9	19.4
2033	21.0	19.9	19.6	20.9	20.5	21.3	21.4	19.1	19.5	21.0	21.1	20.2
2034	21.7	20.2	19.3	19.3	20.7	19.7	18.5	19.2	19.7	19.9	22.9	19.2
2035	19.8	18.8	18.6	20.6	20.3	19.8	20.2	20.5	19.7	17.6	20.4	19.8
2036	19.3	20.9	20.0	19.6	19.3	20.7	20.7	20.4	19.6	19.2	23.2	18.0

Year	Ensemble member											
	Model01	Model04	Model05	Model06	Model07	Model08	Model09	Model10	Model11	Model12	Model13	Model15
2037	20.0	20.5	20.8	20.3	20.4	19.4	19.5	20.2	19.8	18.9	20.1	17.8
2038	20.2	19.3	20.2	21.2	18.8	22.0	21.5	21.2	19.2	21.7	19.9	20.7
2039	19.9	18.9	19.9	19.8	20.0	21.2	21.0	20.4	20.0	21.7	20.9	18.4
2040	19.6	18.0	19.6	19.5	20.1	22.1	20.8	20.7	20.1	20.2	18.9	21.8
2041	21.9	19.1	19.5	20.5	20.3	20.6	21.0	19.0	21.8	19.3	21.7	20.5
2042	20.6	20.6	19.1	19.5	19.5	21.7	19.4	20.5	20.8	20.6	20.9	19.8
2043	20.7	19.3	20.0	18.5	19.8	22.4	20.5	19.4	20.5	20.8	19.9	19.8
2044	19.9	20.7	21.0	19.9	19.3	20.3	21.3	20.1	21.5	20.9	21.0	20.0
2045	20.1		20.0	22.2	19.7	19.3		20.1	22.2	22.1	24.5	21.4
2046	21.6		19.0	20.6	20.5	20.7		20.2	21.1	20.2	20.8	18.5
2047	21.7		19.0		20.1	20.4		20.9		20.2		20.2
2048	19.7		21.6		20.7	20.5		18.9		20.6		19.6
2049			21.3		19.6	24.0		20.8		20.6		21.0
2050			20.2			20.2				19.8		19.9
2051										22.5		21.2
2052										19.8		

2. Using this data, T_{max} was identified, which is the highest maximum air temperature projected by each ensemble member over the 20-year GWL period, per GWL, i.e., the maximum average-UK temperature per GWL. This was done to represent the highest projected temperature for each GWL. below shows the T_{max} values according to each ensemble member, for each year over the 20-year period spanning the point at which the GWL is expected to be reached, per GWL. It highlights the minimum, median, and maximum T_{max} values that were used to select the ensemble members. A white to red colour gradient has been used here to show the spread of outcomes between the individual ensemble members, highlighting the influence of climate variability on the extreme temperatures seen across the ensemble. The T_{max} values shown in the table appear relatively low for 'maximum' or 'extreme' temperatures because the values are averaged across the UK[11], and bias correction was conducted to the data (as outlined previously in this section), potentially skewing the results.

Table 19 Tmax value and projected year it is reached, per ensemble member, per GWL (based on average UK-wide Tmax)

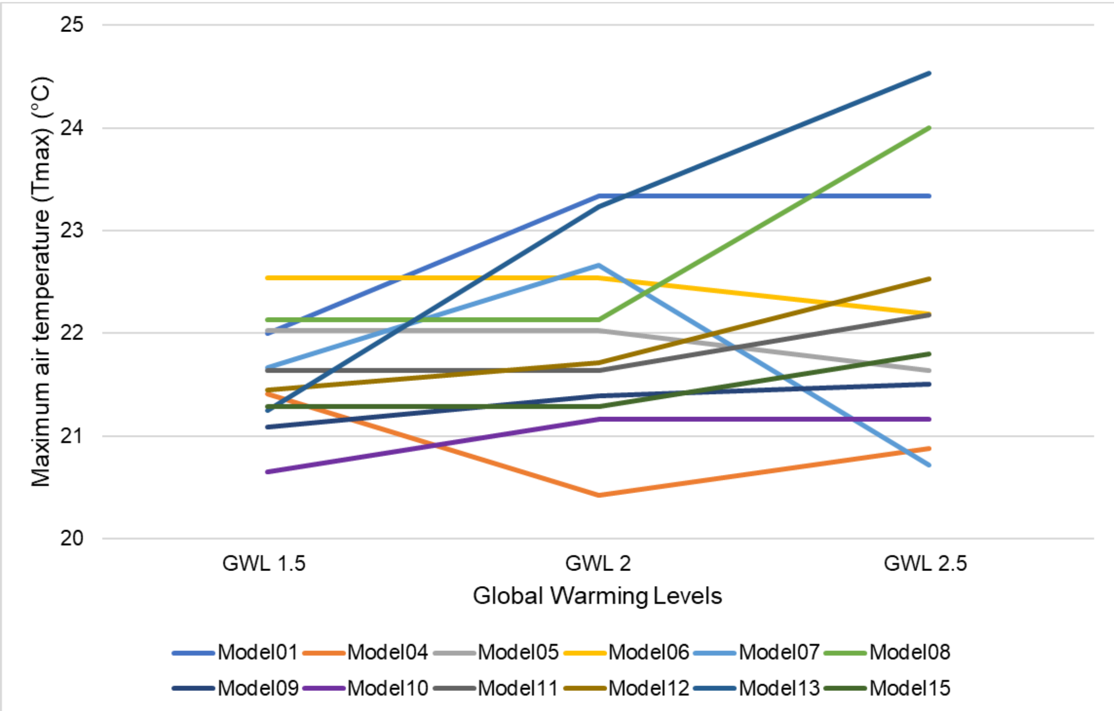
Model	GWL 1.5°C		GWL 2°C		GWL 2.5°C	
	Year of maximum	T_{max} (°C)	Year of maximum	T_{max} (°C)	Year of maximum	T_{max} (°C)
Model01	2025	22.0	2032	23.3	2032	23.3
Model04	2012	21.4	2029	20.4	2036	20.9
Model05	2022	22.0	2022	22.0	2048	21.6
Model06	2026	22.5	2026	22.5	2045	22.2
Model07	2022	21.7	2028	22.7	2048	20.7
Model08	2025	22.1	2025	22.1	2049	24.0
Model09	2016	21.1	2033	21.4	2038	21.5
Model10	2028	20.7	2038	21.2	2038	21.2
Model11	2020	21.6	2020	21.6	2045	22.2

[11] Different approaches were tested to determine a suitable method for ensemble member selection. Guidance was provided by the CCC for a potential selection process that is currently being developed. This option for selecting members involved assessing the rate of change in T_{max} between the years at which each GWL is reached, per member, and using this information to determine the minimum, median, and maximum member based on their rates of change. This suggested approach led to some unexpected results, e.g. showing extreme heat in the UK to be less severe in the longer term, i.e. in a 2.5°C world, according to the 'maximum' member, in comparison to the shorter term, according to lower GWLs. Due to time constraints limiting the ability to resolve these challenges for this study, an alternative method was used as outlined above. In this different method, the minimum, median, and maximum outcome across all ensemble members was used, aiming to show the spread of outcomes between the members at each GWL. This is a potential limitation to this study, as the method used does not align with CCC's approach.

Model12	2018	21.4	2038	21.7	2051	22.5
Model13	2014	21.3	2036	23.2	2045	24.5
Model15	2023	21.3	2023	21.3	2040	21.8

3. Per GWL, the minimum, median, and maximum outputs across the ensemble members, and associated years, were identified. The members that produced (1) the minimum output i.e. the lowest projected T_{max}, (2) the median output i.e. the sixth highest projected T_{max} out of 12, and (3) the highest output, i.e. the highest projected T_{max}, per GWL, were selected for this analysis. This method was undertaken to present the spread of potential high-temperature outcomes across all 12 ensemble members, to account for the uncertainty in the projections between the members at each GWL. This spread of outcomes can be seen in above and Figure below.

Figure 15 Annual maximum air temperature (averaged across the UK), per ensemble member, per GWL



The ensemble members selected (e.g. Model01) and the associated years used in the analysis, per GWL, are presented in below.

Table 20 Selected members per GWL

Output	GWL 1.5°C	GWL 2°C	GWL 2.5°C
Minimum	Model10	Model04	Model07
Median	Model12	Model12	Model15
Maximum	Model06	Model13	Model13

Spatial mapping of exposure: The T_{max} projections were mapped, using Geographical Information Systems (GIS), to present the spatial distribution of extreme heat across the UK, in terms of the minimum, median and maximum outcomes for each of the 1.5°C, 2°C and 2.5°C GWLs, using the members and years shown in above. The maps are shown in the following results section (A.2.2).

The T_{max} data was rated on a five-point scale to determine exposure scores that provide an indication of the magnitude of exposure of each 12km^2 grid to extreme heat, by each of the time periods at which the GWLs are reached. The scores are provided on a scale of from 1 to 5, representing low to high exposure, respectively, using the defined threshold for extreme heat in this study, 27°C, as a starting point for the scoring. A temperature below 27°C is rated 1 for exposure, i.e. low exposure. From 27°C and up, the exposure scores are in bands of 5°C, increasing up to 42°C, covering exposure scores of 2 to 4. Any temperature above 42°C is considered as high exposure in this study with an exposure score of 5. This upper threshold has been set, as while these temperatures have not been reached before in the UK, with the maximum temperature reached in the summer heatwave of 2022 being just over 40°C, higher temperatures may be projected to be reached in the future with climate change. The definitions of these ratings, and associated air temperatures, are provided in Figure :

Figure 16 Definition of exposure ratings

Exposure rating	Associated air temperature	Definition of ratings
1	<27°C	Low exposure
2	27-31°C	Low-medium exposure
3	32-36°C	Medium exposure
4	37-41°C	Medium-high exposure
5	>42°C	High exposure

A.2.1.2 Uncertainty

This section outlines the key uncertainties that underpin this methodology and the use of climate projections data within the analysis. Significant uncertainties are associated with the climate projections used, particularly when the data is projected at such a high resolution of 12km grids. As a result, the findings presented in the maps should be considered only as indicative of the range of potential outcomes of extreme heat across the UK at the selected GWLs.

The key uncertainties and limitations include:

Ensemble member disagreement: There is significant disagreement between different ensemble members, as each simulates the climate differently based on different assumptions underpinning each member, resulting in varying projections of different potential futures regarding the magnitude of extreme heat events. This uncertainty has been accounted for using the members with the minimum, median and maximum outcomes to present the spread of projected outputs within the ensemble (shown in the following section A.2.2).

GWLs: There is uncertainty surrounding the future Global Warming Level the world will reach, which is dependent on the success of global mitigation efforts as well as complex climate processes that are difficult for climate models to simulate and therefore account for in projections, including feedback loops and tipping points.

Spatial resolution (12km^2): There is also significant uncertainty associated with using high resolution climate model outputs, and the data presented here, on a 12km^2 grid, is relatively high resolution. Spatial temperature variation often occurs at larger scales. Presenting this data in the form of maps may indicate a false sense of certainty within the findings for each 12km^2 area.

Selection bias: A further limitation to the method used for ensemble member selection is potential selection bias, due to multiple points at which specific information is selected at different stages of the approach. For example, the basis of the ensemble member selection process involved averaging T_{max} across the UK, and then selecting the year over the 20-year period over each GWL that is projected to experience the maximum T_{max}. This approach was undertaken to identify the maximum, median, and minimum outputs across the ensemble to represent the spread of potential outcomes. However, this averaging, and selection of single years, may lead to the results in fact not showing the full range of potential outcomes across the ensemble.

Exposure thresholds: The same temperature thresholds were used for all assets to determine the different levels of exposure, without considering the ambient temperatures at which each energy asset is sensitive to high temperatures i.e. the temperature at which ambient heat is considered ‘extreme’ for each asset. The 27°C threshold is based on the MO definition of extreme heat. The threshold was chosen due to limited information on ambient temperature thresholds for all assets, and for the purpose of consistency throughout the assessment. It was not based on the level at which faults increase in frequency as the analysis of fault data was completed following the analysis of exposure, largely due to the time it took to gain access to the NaFIRS datafiles and as the NaFIRS dataset is limited in its completeness and quality, it was not strong enough to warrant changing thresholds for extreme heat across the rest of the analysis. This is a limitation to this study as different assets will be sensitive to extreme heat at different temperatures.

As the exposure information feeds into the analysis of potential impact, these uncertainties also underpin the method and results of the impact assessment, outlined in Appendix 3.

A.2.2 Results

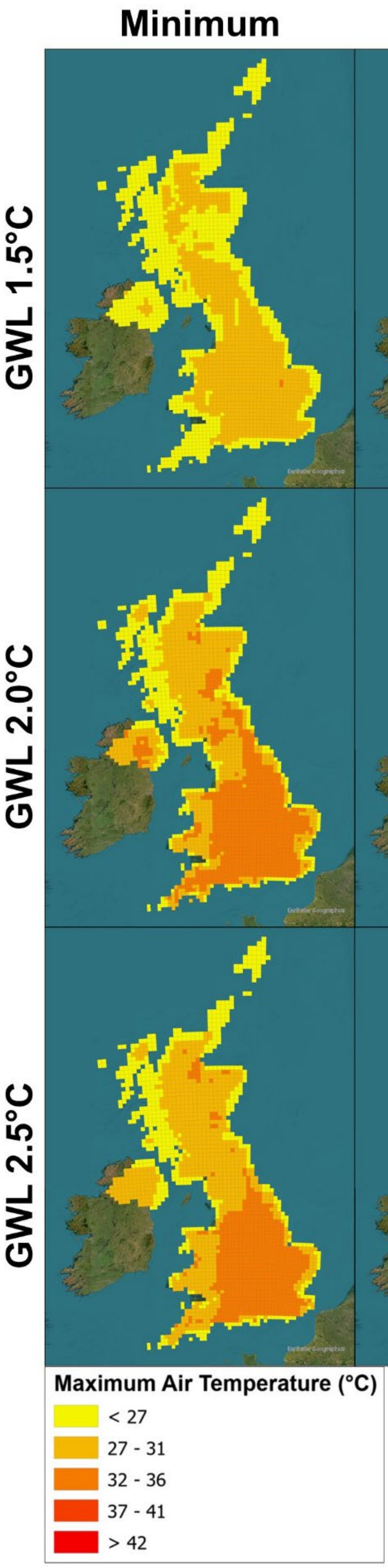
This section presents the results of the exposure analysis, using UKCP18 data to understand projections of extreme heat across the UK and the comparative regional differences in exposure levels.

Figure below shows all outcomes of the exposure analysis, according to the minimum, median, and maximum modelled outputs, for all three GWLs 1.5°C, 2°C, and 2.5°C. This figure shows the potential range in future outcomes of extreme heat across the UK. The projected outcomes differ, depending on the GWL the world reaches, which is reliant on global mitigation efforts. The higher the GWL, the more extreme the maximum air temperature is projected to be. It also highlights the disagreement in outcomes between the ensemble members, as the magnitude of extreme heat that the UK is projected to reach differs across the minimum, median to maximum outcomes. Generally, the maximum outcome per GWL projects the highest maximum temperatures across the UK, although this is not the case for

GWL 2°C for example, where the maximum output is the least extreme, further highlighting the disagreement between ensemble members and range of potential future outcomes of extreme heat in the UK.

Given this uncertainty, the results should only be considered indicative of the potential future of extreme heat in the UK. The full range of outcomes, particularly the most extreme potential outcomes, should be considered when using this information for future planning to adapt UK energy assets to extreme heat.

Figure 17 Exposure to extreme heat for the minimum, median, and maximum outcomes, under GWLs 1.5°C, 2°C and 2.5°C



Appendix 3 – Impact Assessment

A.3.1 Methodology

To identify and spatially map the potential level of impact of extreme heat on energy assets, the exposure scores were overlaid with the ratings of vulnerability as determined in the VRA, using GIS, to identify potential impact scores per 12km^2 grid. This was done using the following matrix in Figure 18.

Figure 18 Potential impact matrix

	Associated temperature threshold (°C)						
Exposure	42+	5	1	2	3	4	5
	37-41	4	0	1	2	3	4
	32-36	3	0	0	1	2	3
	27-31	2	0	0	0	1	2
	Below 27	1	0	0	0	0	1
Potential level of impact			1	2	3	4	5
			Vulnerability				

Figure 19 shows the definitions of the potential impact scores:

Figure 19 Definition of potential impact ratings

Impact rating	Definition of ratings
0	No impact
1	Low impact
2	Low-medium impact
3	Medium impact
4	Medium-high impact
5	High impact

The use of this matrix assumes a linear relationship between exposure, vulnerability and impact, which may not exist. Hence, it is important to consider that the relationship between exposure, vulnerability and impact used in this matrix and subsequent mapping is assumed rather than measured and is therefore a limitation of this study.

Table 21 below helps to qualify the impact scores, and to provide a sense-check that they accurately reflect the temperature thresholds at which impacts to each asset can be expected. The table presents the projected impacts at vulnerability ratings 2, 3 and 4 at different levels of exposure to extreme heat. These projected impacts are then compared with level of impact that could be expected to two technologies at each vulnerability rating, based on evidence from the REA. The explanations for the expected impacts are drawn from text in the vulnerability assessment. The projected impacts are in some cases higher than the expected impacts, and in other cases lower. Overall, this suggests that the relationship between exposure, vulnerability and impact that is assumed in the impact matrix is a good fit for the qualitative assessment conducted in this study.

Table 21 Projected versus expected impacts at different levels of vulnerability and exposure

Asset / vulnerability level	Level of exposure to extreme temperatures (°C)					Explanation for expected impacts
	42+	37-41	32-36	27-31	Below 27	
Projected impacts at vulnerability rating 2	***2***	***1***	***0***	***0***	***0***	
Expected impacts to gas transmission and distribution network (Vulnerability 2)	1	1	0	0	0	Gas pipelines in the UK are currently designed for ambient temperatures between -30°C and 60°C. Extended period of high temperature could have a minor impact but most vulnerable assets are considered to be the supporting IT equipment and instrumentation.
Expected impacts to wind turbines (Vulnerability 2) -	2	1	0	0	0	Heatwaves further increase wind turbines' cooling demands, leading to raise the operational costs, and putting strain on technical and financial capacities. In result, the insufficient cooling systems may also lead to equipment failures or downtime.
Projected impacts at vulnerability rating 3	***3***	***2***	***1***	***0***	***0***	
Expected impacts to solar PV (Vulnerability 3)	2	2	1	1	0	Solar panels are designed to meet international standards, allowing them to operate at ambient temperatures of 50°C, ensuring resilience during high-temperature events; however, efficiency may still decline under extreme heat and heatwaves. Increase in temperature above standard operating levels can reduce the efficiency of solar power

Asset / vulnerability level	Level of exposure to extreme temperatures (°C)					Explanation for expected impacts
	42+	37-41	32-36	27-31	Below 27	
						plants. For every degree rise above 25°C, plant efficiency decreases by 0.2–0.5%
Expected impacts to gas power plants (Vulnerability 3)	3	2	1	1	0	The efficiency of gas power plants is diminished by high air temperatures as systems cool less quickly and efficiently. The efficiency of a gas turbine is more affected by air cooling compared to water cooling, with dry cooling systems facing greater losses as air temperatures rise. This difference becomes more in hot temperatures, where ambient air above 40°C severely limits dry cooling efficiency.
Projected impacts at vulnerability rating 4	***4***	***3***	***2***	***1***	***0***	
Expected impacts to transmission & distribution transformers (Vulnerability 4)	4	3	2	1	0	Higher operating temperatures leads to faster degradation of insulation and cooling oil. To ensure optimal transformer performance, the external ambient temperature must not exceed 40°C at any time and must not exceed a monthly average of 30°C or a yearly average of 20°C/
Expected impacts to switchgears, circuit breakers and other protection devices (Vulnerability 4).	4	3	2	1	0	Switchgears and protection devices capacity decreases with rising ambient temperatures, with continuous current ratings significantly derating above 40°C [Ricardo in-house experts]. Oil-immersed switches and circuit breakers are typically designed for ambient temperatures of up to 40°C, but fluctuations in temperature and

Asset / vulnerability level	Level of exposure to extreme temperatures (°C)					Explanation for expected impacts
	42+	37-41	32-36	27-31	Below 27	
						insufficient cooling can exacerbate their sensitivity and affect reliability.

The impact scores, per vulnerability rating, are spatially presented on maps of the UK. The maps (shown in section A.3.2) do *not* indicate that an energy asset is exposed within each 12km^2 square grid but simply indicate that *if that class of energy asset is present* (of the associated vulnerability rating) in that grid square, then it could be exposed to the hazard and result in the level of potential impact indicated by the score. The definitions of the impact ratings are provided in Figure above. The information shown on the maps is useful for considering where climate impacts to existing energy assets need to be addressed and to inform future planning of the energy system. However, it is key for decision makers to consider the high degree of uncertainty associated with these projections at the resolution of 12km², as the projected spatial trend of potential impact is based on highly uncertain climate model projections. Therefore, the results are only an indication of a range of potential future outcomes and may not be accurate or realised in the future.

A.3.2 Results

This section presents the results of the spatial impact analysis, using both UKCP18 data to map projections of extreme heat across the UK, combined with the vulnerability ratings identified in the vulnerability assessment, to present potential impact to extreme heat and the comparative regional differences.

Figure 20 to 22 below present the potential impact levels to energy assets across the UK for GWLs 1.5°C, 2°C and 2.5°C, respectively. These maps are presented for assets across all vulnerability levels, with scores of 1-5, described as: highly resilient; resilient; potentially vulnerable; vulnerable; and highly vulnerable, respectively. The trend is clear: the more vulnerable the asset and the higher the GWL, the higher the potential impact is projected to be. Southern England is projected to be experience the most severe potential impact across all GWLs and vulnerability levels.

Figure 20 Potential impact level for assets at all vulnerability levels at **GWL 1.5°C**

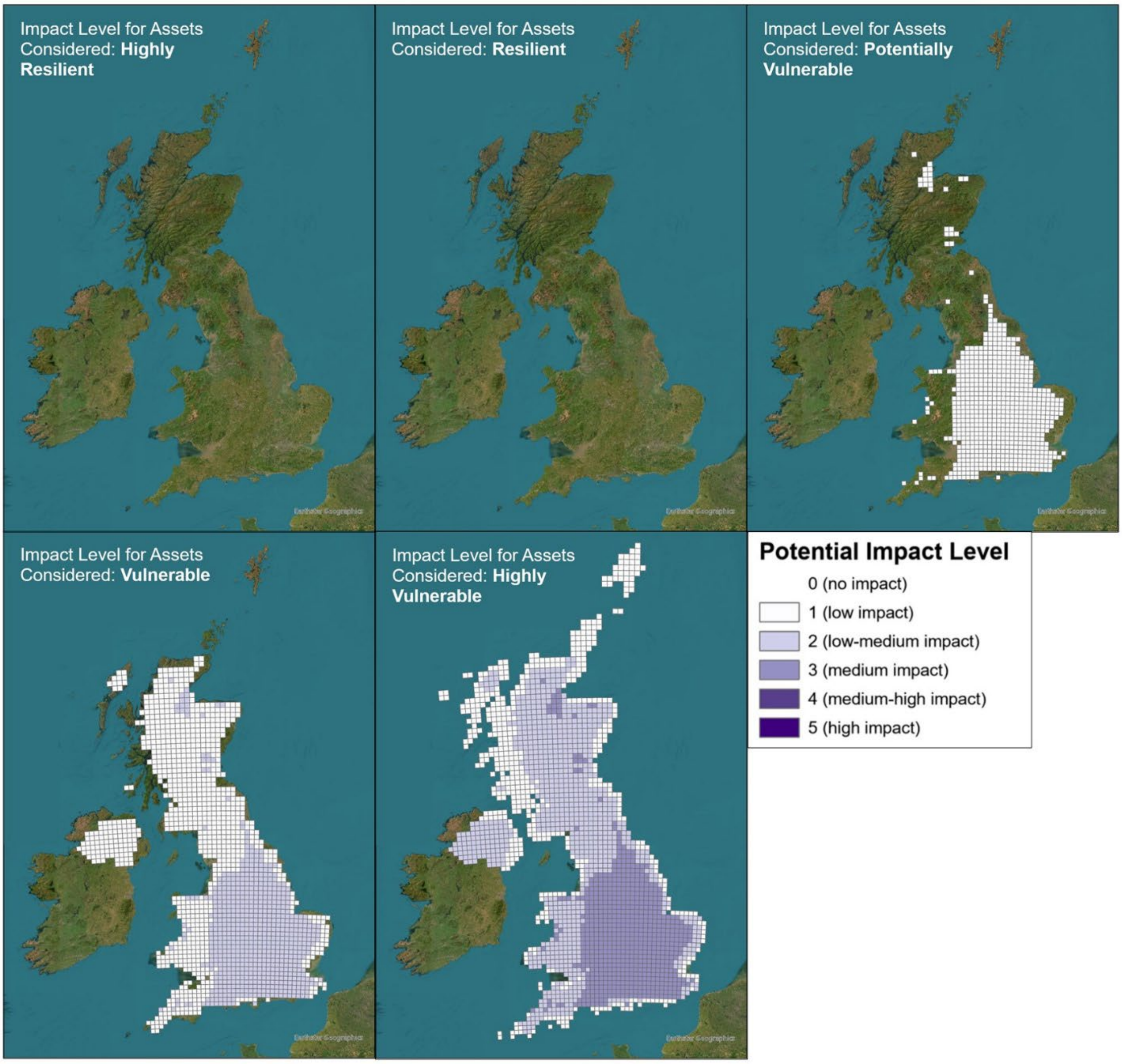


Figure 21 Potential impact level for assets at all vulnerability levels at **GWL 2°C**

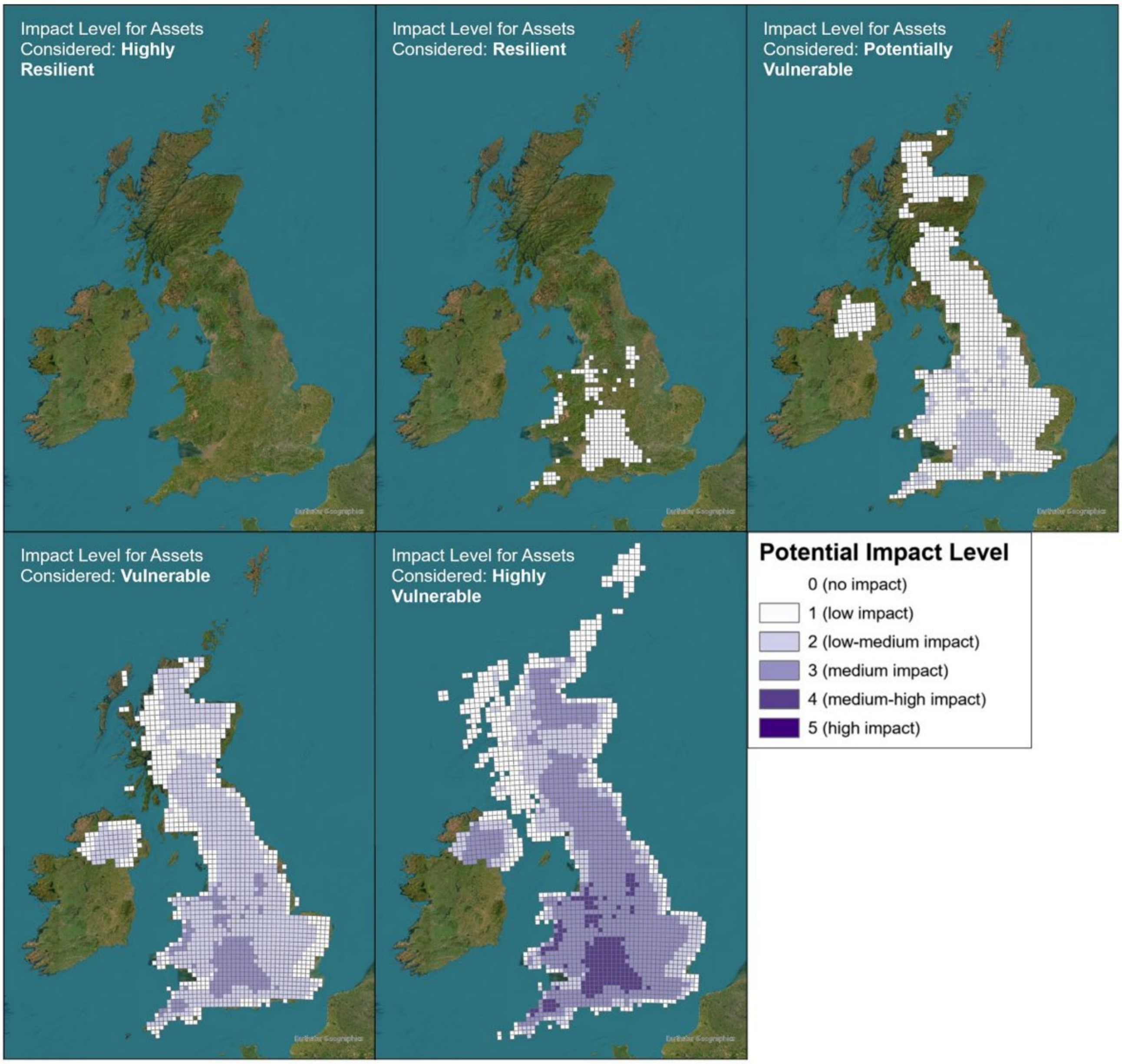


Figure 22 Potential impact level for assets at all vulnerability levels at **GWL 2.5°C**

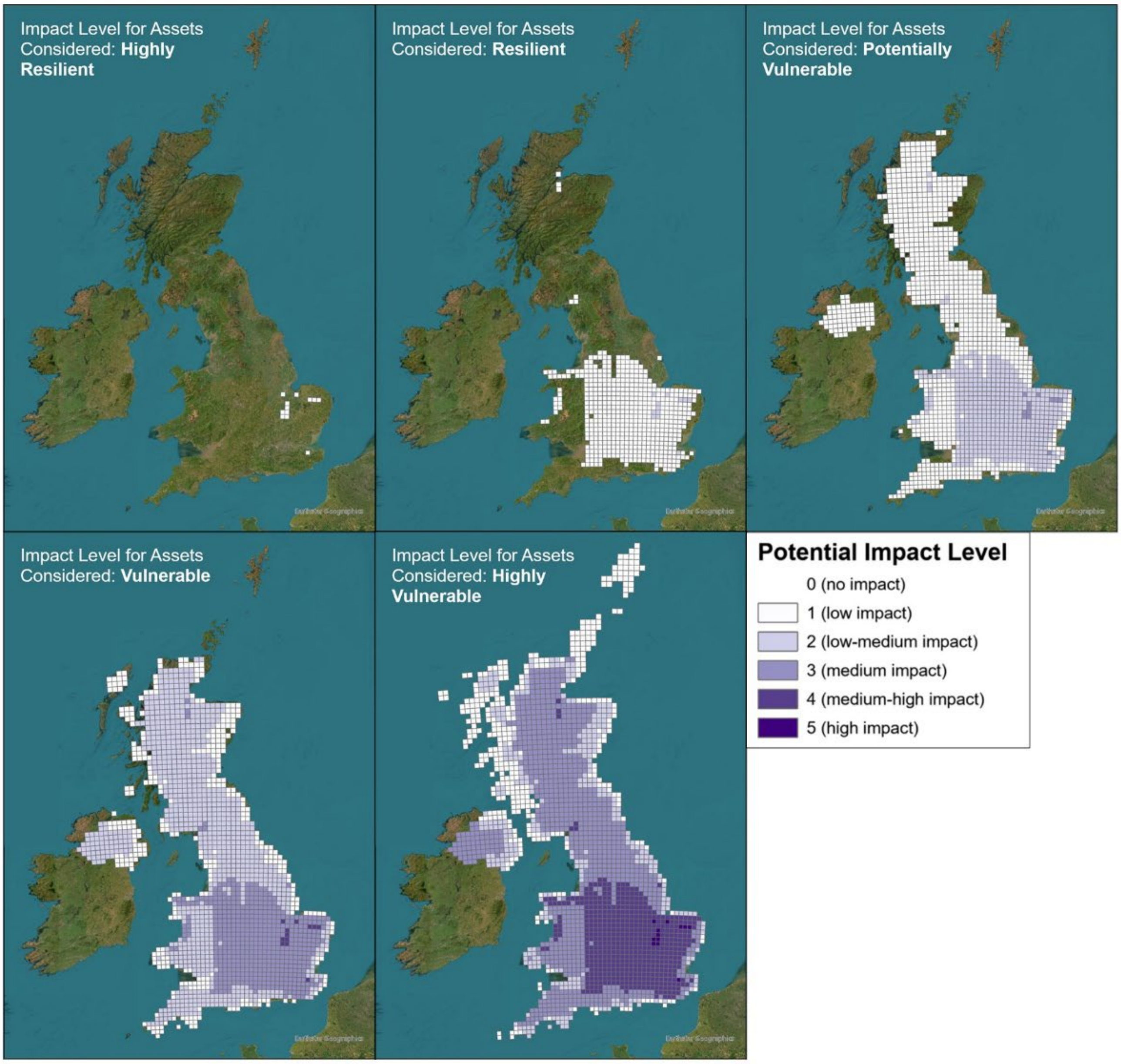
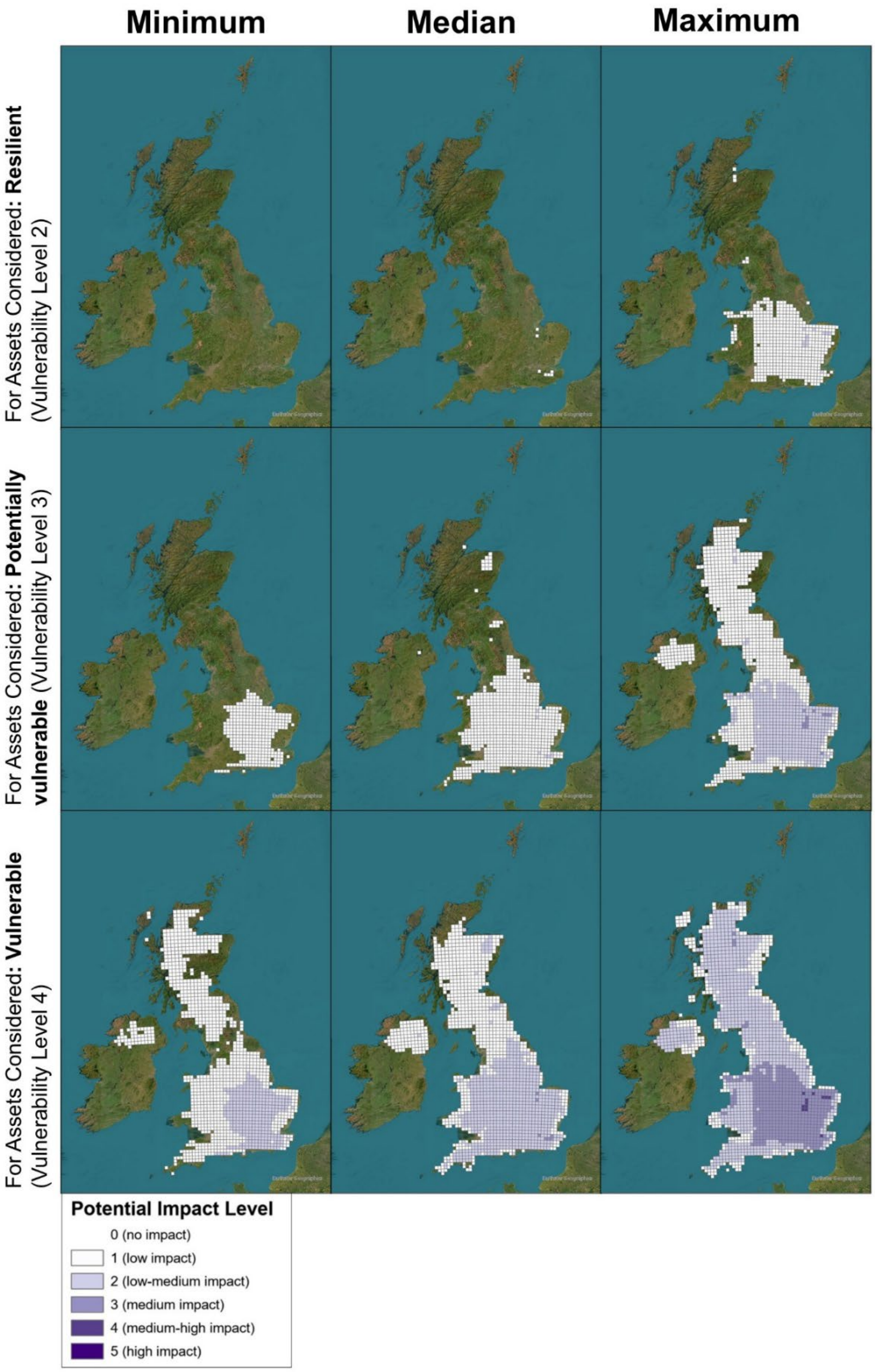


Figure 23 presents the potential impact levels for assets at vulnerability levels 2, 3, and 4, across the minimum, median, and maximum modelled outcomes, under the highest GWL, 2.5°C. This figure highlights the potential range, and therefore the uncertainty, across the projected outputs of potential impact.

Figure 23 Potential impact level for assets at vulnerability levels 2, 3, and 4, for the minimum, median, and maximum modelled outcomes, under **GWL 2.5°C**



Appendix 4 – Predicting temperature related faults within the energy system

A.4.1 Methodology

This section presents the methodology from the exploratory quantitative analysis. The analysis aims to quantify the relationship between weather-related variables and asset failure rates to validate and corroborate the findings from the qualitative risk and vulnerability assessment of this project. By better understanding the relationship between temperature and faults, distribution network operators (DNOs) and government bodies can better understand how faults are expected to materialise (i.e. the number, type, and severity of faults) in future as the climate, and the number of extreme heat events, changes. DNOs can thus invest in the network to be better prepared for the impact of heatwaves.

The first part of this assessment is to investigate whether there is a meaningful statistical relationship between temperature data and electrical asset failures in Great Britain (GB). Visual plots and statistical techniques are used to explore possible relationships in the datasets. Based on these findings, a brief study on the potential use of machine learning techniques to predict asset failures during heatwave periods is presented. A short literature review was conducted to understand the existing research on weather-related faults in electricity systems.

A.4.1.1 Short literature review

A number of research papers have explored the relationship between weather-related events and faults in electricity systems. Electrical asset failures can be caused by many factors including the impacts of storms and hurricanes, earthquakes, lightning, snow, blizzard, accidents, internal damage, aging and degradation, operational factors, deliberate physical damage, and cyber [78], [79], [80]. An estimated 80% of power outages were caused by weather-related events in the US between 2003-2012 [81].

Electrical network faults can be defined through fragility functions that are expressed as faults per km of network in a given area or faults per average length of overhead lines between two poles [82]. The impact of weather-related events on electrical assets can materialise in the short-term, where assets fail in response to an event, or through a long-term cumulative effect, where assets degrade over time in response to long-term exposure to weather-related events [79]. Responses to heat waves on the distribution network are found to depend on the fatigue of cables from thermal stress and a delay in time until the failure kicks in [80].

To define a heatwave, some studies have used the dimensionless indicator Heat Wave Magnitude Index-daily (HWMId) [80]. One definition of a heat wave is when the daily temperature within a 31-day window exceeds a given percentile of the maximum daily temperature in a reference period between 1981-2020 for three or more consecutive days [80].

In the UK, Dunn et al. (2018) use the National Fault and Interruption Scheme (NaFIRS) database to study the risk of distribution network overhead line failures due to windstorm hazards. They define a windstorm when the maximum wind speed exceeds a threshold of 17 m/s. They then define the average number of wind-related faults per windstorm event. They find that the majority of faults occur within a 6-hour period of the peak wind speed of a storm or shortly after. They also find that overhead lines have very low failure rates at windspeeds below 20 m/s, while showing a significant increase in failure rates above wind speeds of 30 m/s [82].

Murray & Bell (2014) use fault data from the three transmission companies (National Grid, Scottish Power, SSE) in Great Britain. Half of the faults were attributed to weather-related events in the GB transmission network, while the remaining faults were categorised as non-weather related. The authors also note that the majority of faults took place on overhead lines, with generally lower rates of failures on other equipment types. They find that there is a strong non-linear correlation between wind speeds, wind gusts and electrical faults. Their results show that 66% of wind-related faults occur in the top 1% distribution of wind gusts, while 90% of wind-related faults occur in the top 20% distribution [83].

Tsioumpri et al. (2021) use a comprehensive set of weather variables to predict faults using data from the Northern Powergrid DNO. They use a machine learning classification model to predict a binary outcome (faults vs no faults). They also predict multi-class outcomes with no fault and the different fault causes as prediction classes. The dataset contains data on faults together with generated no faults data points for 24 hours and 1 week before the fault data point, when the no fault conditions happened to be true at those times. They find that Linear

Discriminant Analysis and Random Forest Classifier are the best performing models trained on the High Voltage (HV) data, with an accuracy of 0.792 and 0.728, respectively. The Gradient Boost classifier was the best performing model on the Low Voltage (LV) data, with an accuracy of 0.82. They found that applying ensemble classifiers to the combined dataset of HV and LV resulted in higher accuracy than the individual classifiers [79].

Mazza et al. (2024) find that an increasing number of faults take place in the distribution network during heat waves in urban areas, using data from a city in north-western Italy. They find that some of the faults attributed to high temperatures do not occur during daytime when the temperature is highest but can occur during the night due to the lag between high temperatures and the fault materialising [80].

Rizeakos et al. (2023) use synthetic data to simulate fault occurrences and develop machine learning models to identify the location of the faults and classify the fault into 11 different types [84].

Fatima et al. (2024) carried out a comprehensive review of the ability of machine learning models to predict power outages during hurricane events, setting out the steps and choices researchers need to conduct research on this topic [78].

A.4.1.2 Datasets

This section describes the data used in the analysis. To explore the statistical relationship between ambient air temperatures and electrical faults, the first step was to review relevant datasets. Four electrical faults datasets were obtained:

- **REMIT dataset:** this contains self-reported faults data from generation, transmission and consumption units in the GB wholesale market.
- **NaFIRS dataset:** The National Fault and Interruption Scheme contains fault data from the distribution network companies in the UK. The dataset we could access contained data from 2018 to 2022.
- **Northern Powergrid (NPG) faults dataset:** Distribution network faults provided by Northern Powergrid DNO.

- **Electricity North West (ENWL) faults dataset:** Distribution network faults provided by Electricity North West DNO.

Based on an exploration and review of the different data sources, it was decided that the NaFIRS dataset would be the most suitable dataset to choose for the analysis. This was based on its relatively higher quality dataset together with its coverage across the UK. The REMIT dataset lacked a high reporting quality, while the NPG and ENWL datasets lacked large geographical coverage.

The NaFIRS dataset contained data between 2018-2022 and was grouped by failures in different parts of the network:

- 132+ kV network
- the high voltage (HV) network (11-66 kV)
- low voltage (LV) network (<11kV),
- planned outages (PA)
- short interruption (SI)

It includes data on the time of the fault, the direct cause and contributing cause category, the components involved, the district in which the fault occurred, as well as data on total consumers involved, total hours lost and total max demand at the time of the fault. Table 22 below shows the top 25 cause messages in the HV network of the NaFIRS dataset. “Deterioration due to Ageing or Wear (excluding corrosion)” is the most frequent cause with over 51,000 fault messages, while “Solar Heat” is number 24 on the list, with 931 messages.

Table 22 The top 25 cause messages from the HV network data in NaFIRS

No.	Cause message	Number of faults	Percentage of total faults
1	Deterioration due to Ageing or Wear (excluding corrosion)	51479	33.4%
2	Wind and Gale (excluding Windborne Material)	18208	11.8%

No.	Cause message	Number of faults	Percentage of total faults
3	Cause Unknown	16453	10.7%
4	Operational or Safety Restriction	8444	5.5%
5	Lightning	5336	3.5%
6	Falling live trees (not felled)	5308	3.4%
7	Birds (including Swans and Geese)	5306	3.4%
8	Interruption to remove local generator or restore temporary connections	4836	3.1%
9	Premature Insulation Failure	4790	3.1%
10	Causes Unclassified in this Table	2319	1.5%
11	Growing trees	2263	1.55
12	Extension of Fault Zone due to Fault Switching (including ASC held faults)	2261	1.5%
13	Vermin, Wild Animals and Insects	1964	1.3%
14	Corrosion	1670	1.1%
15	by Private Individuals (excluding 49 and 56)	1635	1.1%
16	involving Farm Workers or Farm Implements	1557	1.0%
17	Falling dead trees (not felled)	1494	1.0%
18	Faulty Installation or Construction	1459	1.0%
19	by Unknown Third Parties	1434	1.0%
20	Windborne Materials	1337	0.9%

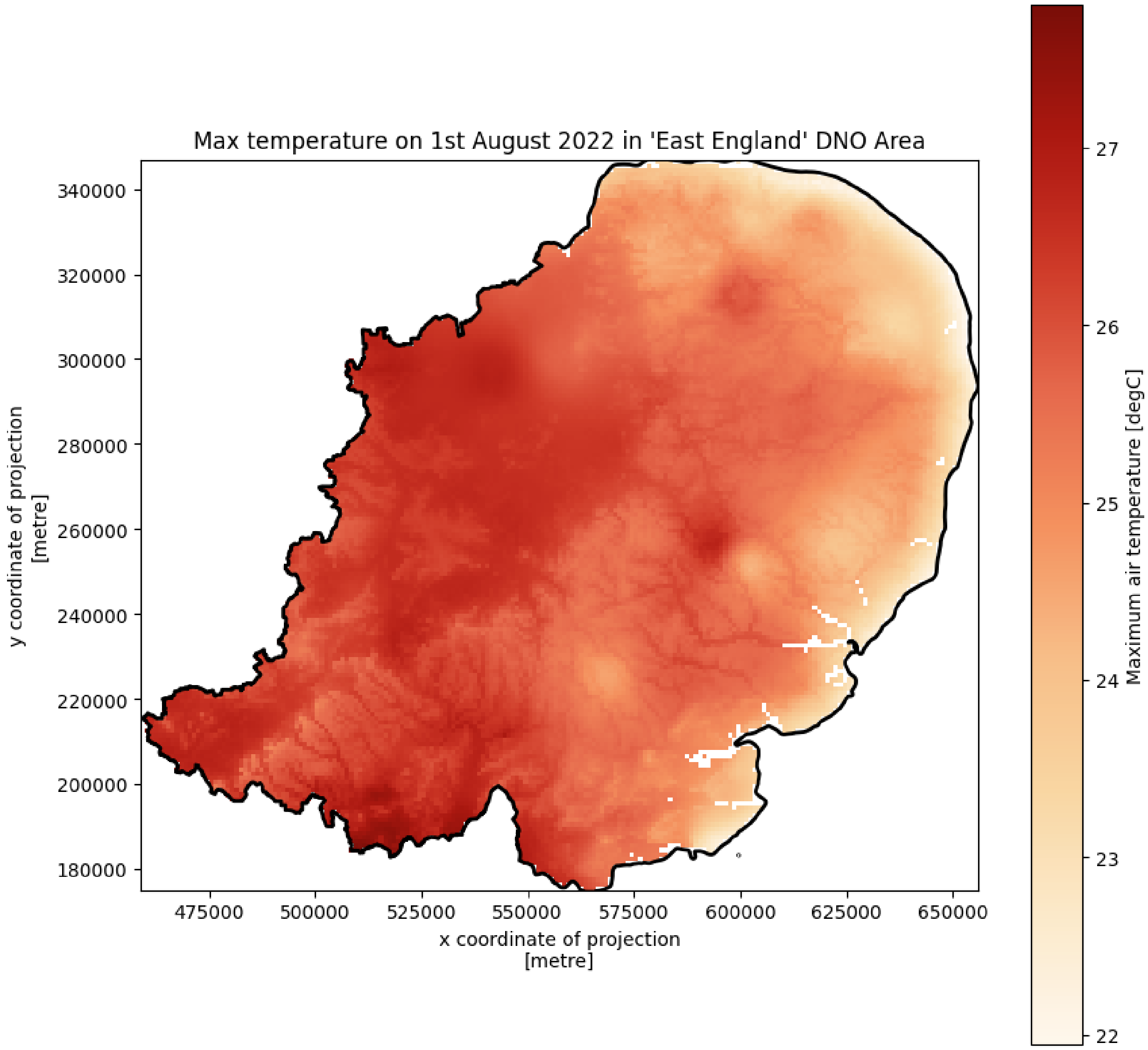
No.	Cause message	Number of faults	Percentage of total faults
21	by Private Developers or their Contractors	1306	0.8%
22	Faulty Manufacturing, Design, Assembly or Materials	1250	0.8%
23	by Other Third Parties	958	0.6%
24	Solar Heat	931	0.6%
25	Fault on DNO Equipment Faulting Adjacent Equipment	909	0.6%

Weather-related datasets are required to explore the relationship between historic temperatures and electricity system faults. The UKCP portal was accessed to explore datasets on historical temperatures around the UK. However, the Centre for Environmental Data Analysis (CEDA) Archive platform provided a more comprehensive and easily accessible platform to access the data and was thus used instead. The CEDA Archive contains the Had UK-Grid Gridded Climate Observations on a 1km grid over the UK from 1863 to 2023. The dataset provides the following daily data at the 1km spatial resolution:

- Minimum air temperature (Celsius)
- Maximum air temperature data (Celsius)
- Rainfall (mm)

Daily data was downloaded between 2018 and 2022 for each DNO using the centre point coordinates of each DNO area. The coordinates were found by using the boundaries data of each Distribution Network Operator (DNO) License Areas and calculating the centroid of each boundary dataset. Figure shows the temperature variation within the East England DNO area on a summer's day. It shows a temperature variation between 22 and 27+ degrees. Hence, picking the centroid for each DNO area introduces a margin of error in terms of the maximum temperatures across the DNO area.

Figure 24. Heatmap of the max temperature on an arbitrary summer's day in the East England DNO License Area



A.4.1.3 Statistical analysis

In order to explore the frequency of faults occurring at particular temperatures, the fault dataset was transformed into discrete interval bins based on the maximum temperature of the day in which the fault occurred. The bins capture a 2°C interval each, between the full range from -10.0 to +40.0 °C. This is shown in Figure below. The highest number of faults occur around 10-12 degrees, with a low number of faults taking place at very low and high temperatures. Figure 26 shows a zoomed in version of Figure 25, where the failure count for temperatures above 28 degrees can be inspected more clearly. It shows that although the failure count is much lower at higher temperatures, it is non-zero up to 40 °C. It should be noted that this is the absolute fault count. The figures do not take into account the distribution of days for which those maximum temperatures occurred, and thus the high number of faults in the range 10-20 degrees is due to the high number of days where the maximum temperature is in that range. We therefore need to normalise this by the number of days in which different maximum temperatures occur.

Figure 25 Number of outage events in each temperature bin

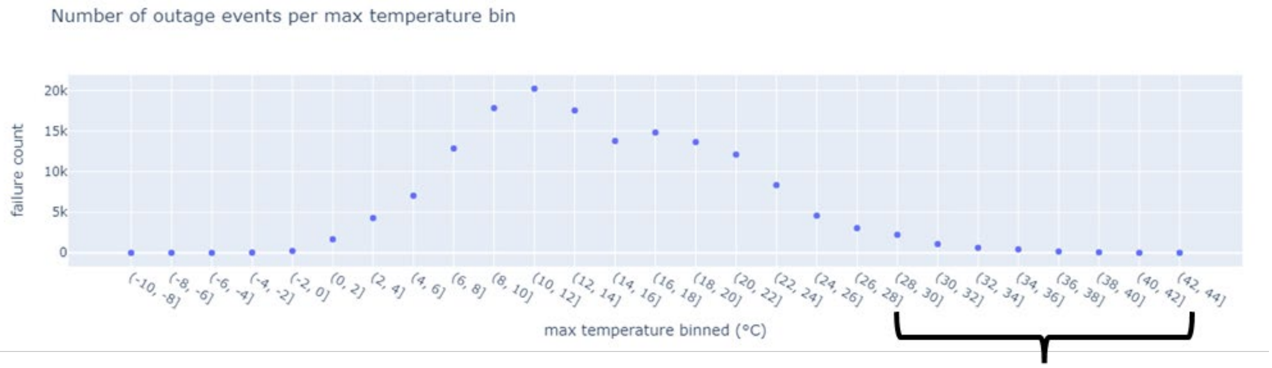
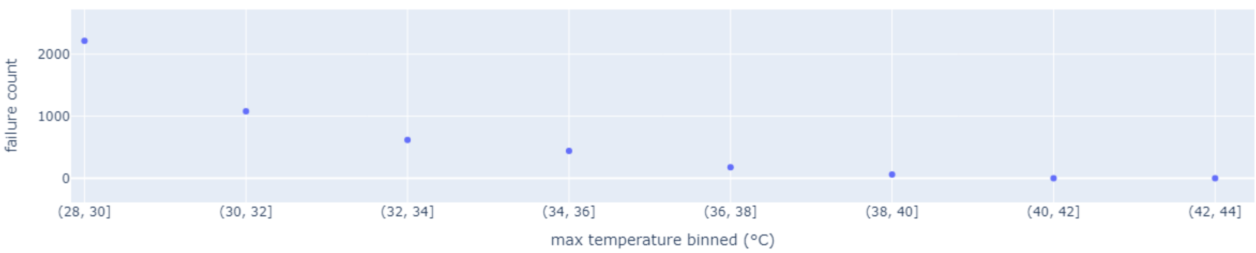


Figure 26 Number of outage events in each temperature bin – zoomed in at temperature range 28+ degrees



To normalise the plots, we first need to transform the temperature data into 2-degree intervals. This is plotted in Figure below. Figure shows the same plot zoomed in on temperatures above 28 degrees.

Figure 27 Number of days within each 2-degree bin of daily max temperature

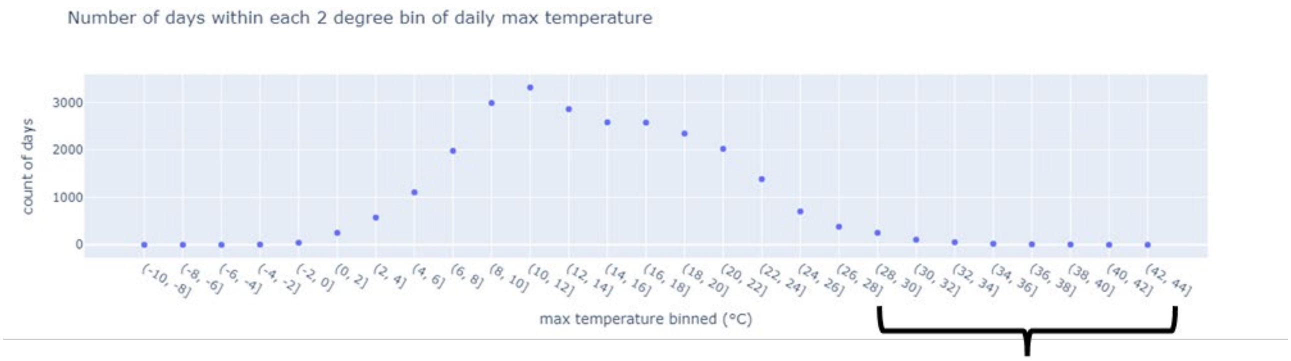
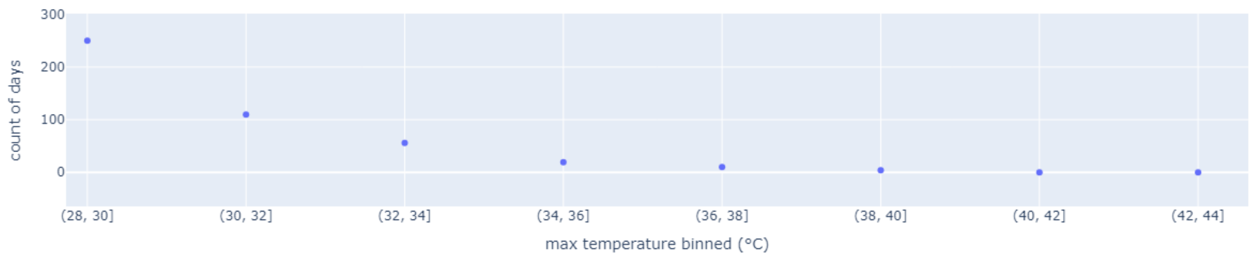


Figure 28 Number of days within each 2-degree bin of daily max temperature – zoomed in at temperature range 28+

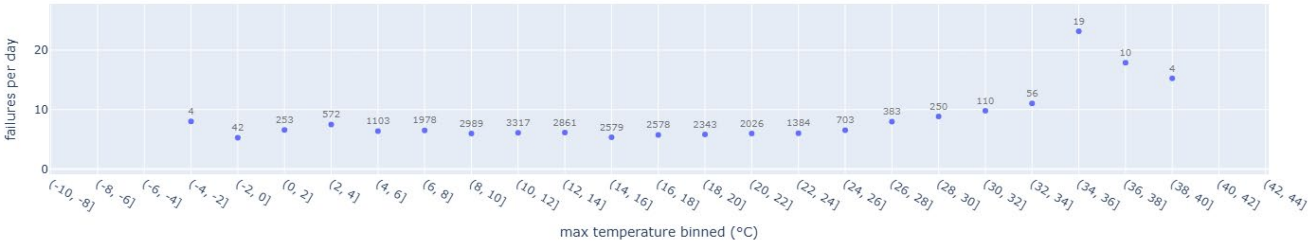


As seen in the figures above, the highest number of faults coincides with a high number of days with that temperature. Hence, the temperature distribution can be used to normalise the number of faults occurring per day within a temperature threshold. In order to find the rate of outages per day for a given temperature interval, the following calculation is used:

$$\frac{number\ of\ outages \big/ temperature\ interval}{number\ of\ days \big/ temperature\ interval} = \frac{number\ of\ outages}{number\ of\ days}$$

Figure shows the average number of outages per day in a given temperature bin. For example, most days where maximum temperatures are in the range of 8 to 24 degrees, an average of 5 faults occurred in each DNO area. The figure shows that the fault rate increased above 22 degrees and reached over 15 average faults per day at temperatures above 34 degrees. It is important to note there are much fewer days with temperatures above 34 degrees, for which the exact failure rate at high temperatures has a larger degree of uncertainty.

Figure 29 Number of outage events per day in each bin



A.4.1.4 Machine learning study

Machine learning methods can be used to train a model to predict a target variable based on a number of features that are inputs to the model. For this study, the target variable is the number of faults occurring on a day, while the feature datasets are weather-related variables that can explain some of the faults occurring. Daily maximum temperature, daily minimum temperature and daily rainfall make up the first three features. In addition, feature engineering was deployed. Additional variables were engineered to try to capture cumulative or delayed effects of high temperatures that may contribute to faults. The following features were engineered:

- Difference in maximum temperature from the day before
- Difference in minimum temperature from the day before
- Difference between the maximum and the minimum temperature
- Max temperature on the day before
- Sum of the max temperature of the three previous days
- Heatwave indicator variable (1 if the three preceding days all had max temperatures above 27, and 0 otherwise)

Machine Learning Methods:

To predict electrical faults, we chose to use a supervised machine learning technique that can learn the relationship between the features dataset and the target variable. Both regression methods and classification methods can be used to predict faults. Regression methods predict a continuous variable, such as the number of faults predicted on a given day, while the classification methods predict which class an observation falls within. This could be a binary class (fault, no fault) or a multi class (fault from heat, fault from wind, no fault, etc.). The regression method was chosen as it allows for predicting the aggregate number of faults in a day, which was considered more useful than predicting the failure of a particular asset.

Model Selection:

We tried several machine learning techniques to find the model with the highest predictive power. Different regression models deployed included linear regression, random forest regressor, and gradient boosting trees.

To validate the performance of the model on unseen data, the features and target variable datasets were split into training and testing samples. Out of the 25,000 observations, the first 80% of the sample was used for training while the remaining 20% was kept as a holdout sample.

A grid search was conducted to find the optimal hyperparameters for each of the models. The mean squared error was used as the performance metric. For the Random Forest Regressor, the grid search was used to search over the hyperparameter space of number of estimators and max depth of the trees. For XGBoost, the search looked at the learning rate, number of estimators, max depth of each tree, and alpha as a regularisation term. The mean absolute error (MAE) and mean squared error (MSE) were used to evaluate the performance of the different models. The validation of the different models are shown in Table 23 below.

Table 23 Validation of different models

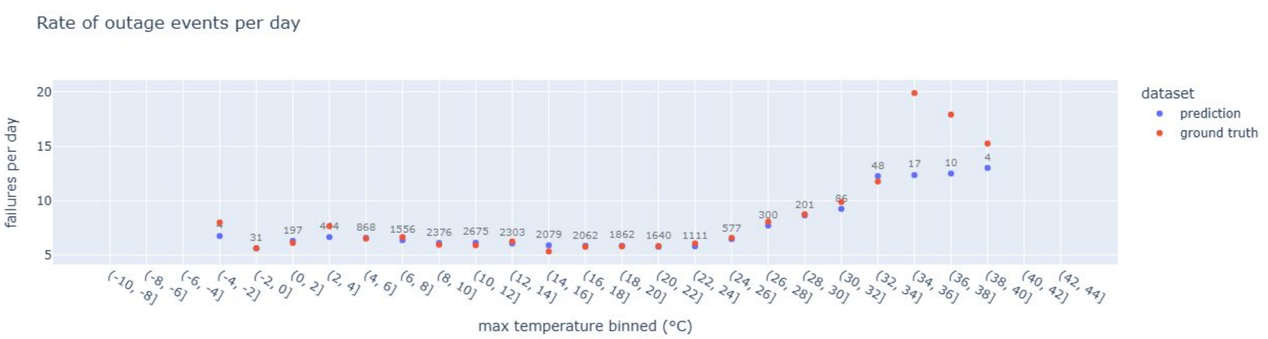
Model	Mean squared error (MSE)	Mean average error MAE)
Linear regression	58.78	4.11
Random Forest	58.57	4.12
XGBoost	57.94	4.16

Although the Random Forest Regressor does not have lowest MSE or MAE, it is the model that scores second best on both MSE and MAE and is thus considered the better performing model across the two-evaluation metrics.

A.4.2 Results

This sub-section presents the results of the machine learning study. The Random Forest Regressor model was used to predict faults in each DNO based on the daily temperature and rainfall in that specific DNO. The predictions were then aggregated across DNO licence areas and placed into bins based on the max temperature variable. Figure 30 below shows how the model predicts based on the High Voltage (HV) data it was trained on. In general, the model shows a good fit with some deviation at the high temperatures (34+°C). The numbers above the points are the number of observations (days) in each bin, which is equal across the prediction and ground truth sample.

Figure 30 Prediction on HV training set



To understand how the model performs on data that it has not seen before, the features in the test dataset were used to predict faults. Figure 31 below shows how the model predicts faults based on data in the test set. It manages to correctly predict most failure rates between -2 °C and 32 °C. However, it predicts a smooth increase above 32 °C while the ground truth in the test sample jumps around between 32 and 36 °C. This was explored and was found to be a result of the limited data available in this temperature range and the randomness with which the test sample is split from the overall sample. This highlights the need for a dataset with more observations above 30 °C.

The same analysis is undertaken for the Low Voltage (LV) dataset. Figure 32 shows that that the model struggles to fit as well to the LV training dataset. It is able to fit the forward sloping pattern seen between 22 and 32 °C, but then struggles to correctly predict faults on days with temperatures above 34 °C. As these temperature bins have significantly less observations in them, not perfectly fitting to the training data can be seen as evidence that the model does not overfit to the training data.

Figure 31 Prediction on HV test set

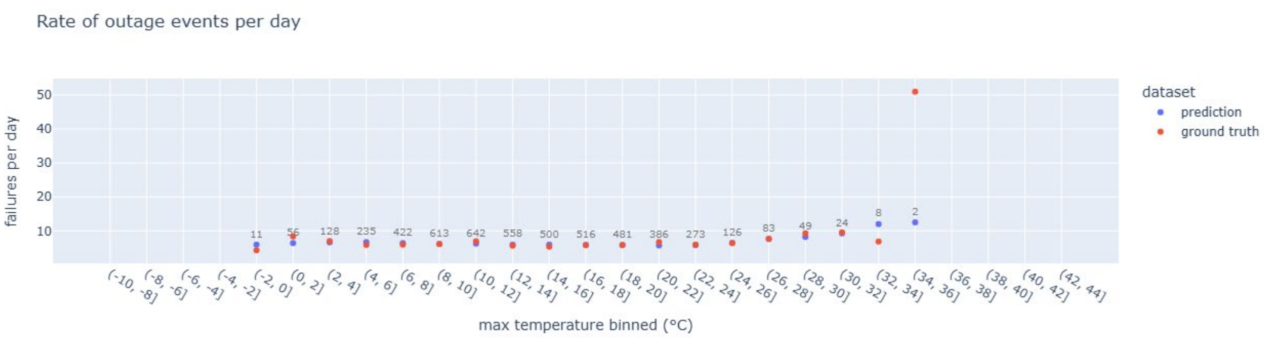


Figure 32 Prediction on LV training set

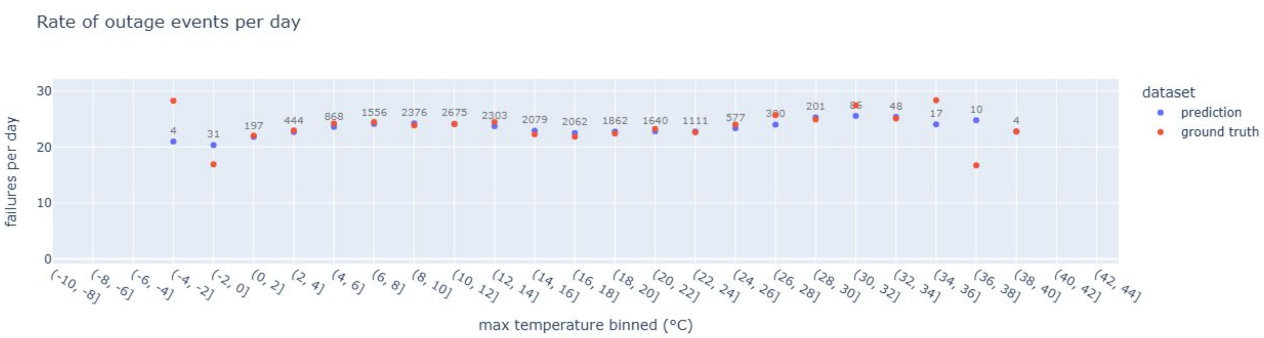


Figure 33 shows the model's predictions on the LV test dataset. It is predicting a slight upward trend from 22 °C and higher but struggles to correctly predict the failure rate at 32 to 34 °C. However, as this datapoint is significantly lower than the other points in the high temperature region, this can be due to the specific test sample generated and varies based on the underlying test sample. The LV data does not show a clear upward trend at temperatures above 30 degrees, and thus failures in the LV network may not be correlated with high temperatures.

Figure 33 Prediction on LV test set

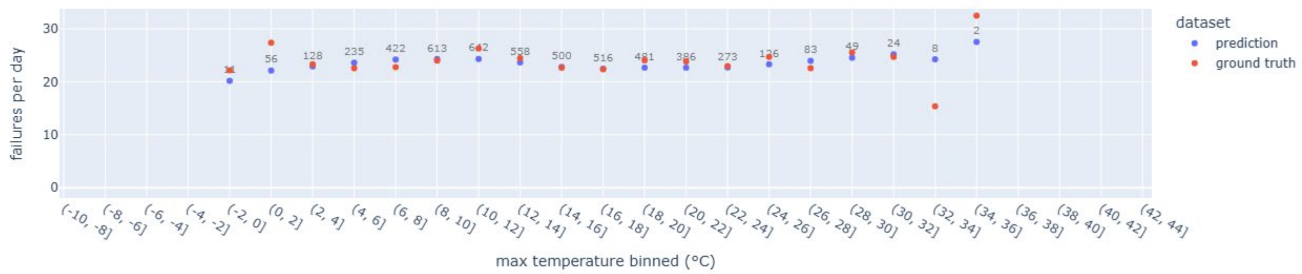


Figure 34 and Figure 35 below show the same plots as shown in Figure 31 and Figure 33, respectively, but only the prediction. Both figures predict an upward sloping relationship between maximum temperature and number of faults in the HV and LV networks. The increase is more pronounced in the HV network, which may be attributed to more of the network being overhead lines over ground rather than cables underground, which is more common for lower voltage networks. The prediction in the LV network data is limited by a lack of a clear positive relationship between temperature and faults data.

Figure 34 Predicted faults in the HV network.

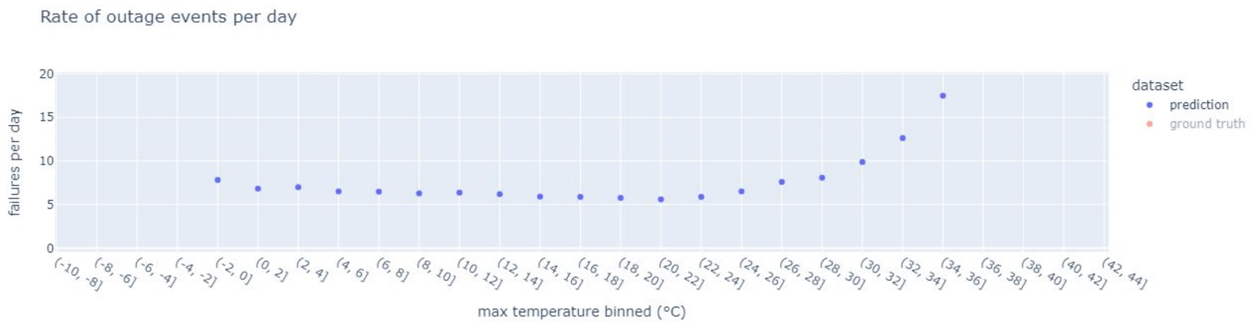
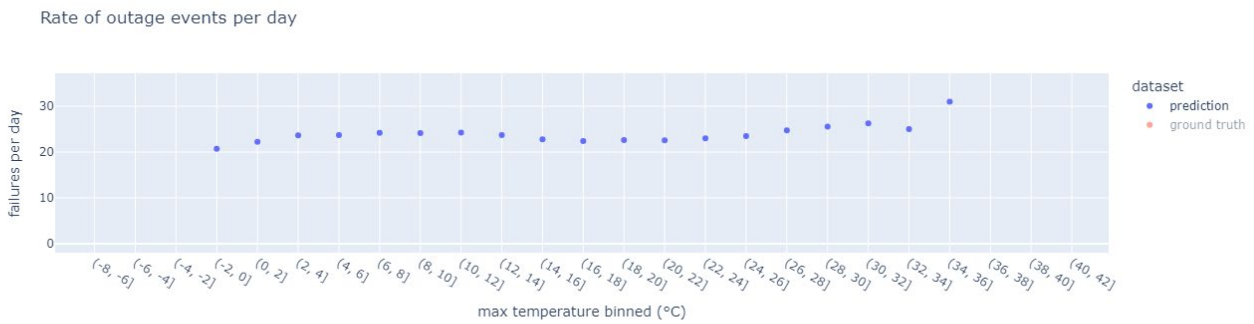


Figure 35 Predicted faults in the LV network.



A.4.3 Limitations of the results

There are several limitations to these results. First, the exact temperature at the location of an asset failure is not captured; instead, temperature at the centre point of the DNO license area is used to capture the temperature in a given DNO area. Using 1km data also introduces temperature variability within each DNO area, and it is possible that averaging across all 1km data points in a DNO and smoothing out this temperature variation could improve the results. While further geographical disaggregation could provide more nuanced results for each DNO Area, this would come at the cost of reducing the number of observations available in each grouping. Increasing the number of years of data may provide additional data points that could allow for conducting a more geographically focused analysis using more local temperature variables.

It is also worth noting that the statistical relationships found in the results do not imply a causal relationship between high temperatures and asset failures. Additionally, it is possible that heat affects generation assets in ways that reduce their efficiency, which is not captured by the failure variable, potentially understating the broader impact on the assets. The vulnerability risk assessment (VRA) provides more detailed insights into this issue.

Generation companies and DNOs have incentives to build and maintain assets that are resistant to failure in order to maximise the revenues from the asset. Theoretically, they should maintain their assets such that the marginal cost of maintenance is equal to the marginal benefit of operating the asset. DNOs are exposed to incentive-based regulation (RIIO) that incentivises them to build and maintain the distribution network to a given standard to maximise their profits.

A.4.4 Key challenges around the quantitative assessment

Accessing high-quality faults datasets was a challenge. The project team started off with the REMIT dataset, and it became clear that the quality of this dataset was not sufficient, and a search for additional datasets began. The process of obtaining access and permission to use DNO faults data was lengthy and in the end the project team was only able to access data from two DNOs (NPG and ENWL). The NaFIRS dataset was also a challenge to access but was eventually shared through one of the project partners.

Having access to NaFIRS data before 2018 would increase the amount of data available to train the model and could help increase the robustness of the results. More granular location data could ensure the mapping between the location of the asset failing and its local temperature could be improved. Adding additional data from countries with hotter climates could significantly increase the sample with high temperature days. Adding additional weather-related variables, such as wind speed, wind direction and sun radiation, could improve the model performance further. However, these variables were not easily accessible in the same daily datapoint format on the CEDA portal.

Appendix 5 – Extreme heat and the UK's future energy demand

A.5.1 Methodology

Following the initial REA review of publications on the direct impact of extreme temperatures on energy assets, it was determined that a complimentary literature review should be carried out to assess the nature of indirect impacts which could arise from climate related temperature rises and the increasing frequency and severity of heat waves. It was identified that these climate impacts may result in increased air conditioner and other active cooling usage, which would in turn drive higher electricity demand and potentially result in new peak loading patterns. The review carried out examined available grey literature publications to assess the existing knowledge base covering UK cooling demand, both present and projected for the future. The aim of this review was to attempt to find answers for the following unknowns: what existing literature has covered cooling future energy scenarios (FES); what cooling demand pathways are anticipated under these FES; to what extent is the impact of cooling driven electricity load growth understood for various FES, and how to these intersect with the findings of the direct impact assessment carried out; what adaptation measures have been identified to help address these indirect impacts; and what are the knowledge and data gaps that must be addressed to better understand this topic.

A.5.2 Literature Review

This literature review was carried out to assess the UK future energy scenarios, with a specific focus on the indirect sensitivities to the UK electricity system resulting from anticipated changes in energy demand for cooling.

Globally, about 20% of electricity consumed is for cooling buildings. Total electricity for cooling is expected to triple by 2050, driven by rising temperatures and incomes [6]. Active cooling of buildings represents a potential adaptation option to address climate risks to health, productivity, etc. caused by heatwaves. However, the dramatic increases in electricity demand driven by active cooling are likely to create additional challenges for electricity systems around the world.

The literature review examined the forecasted future electricity demand for cooling in the UK, and whether the UK electricity system could cope with higher magnitude spikes in cooling demand resulting from future heatwaves, as well as identifying the existing adaptation options.

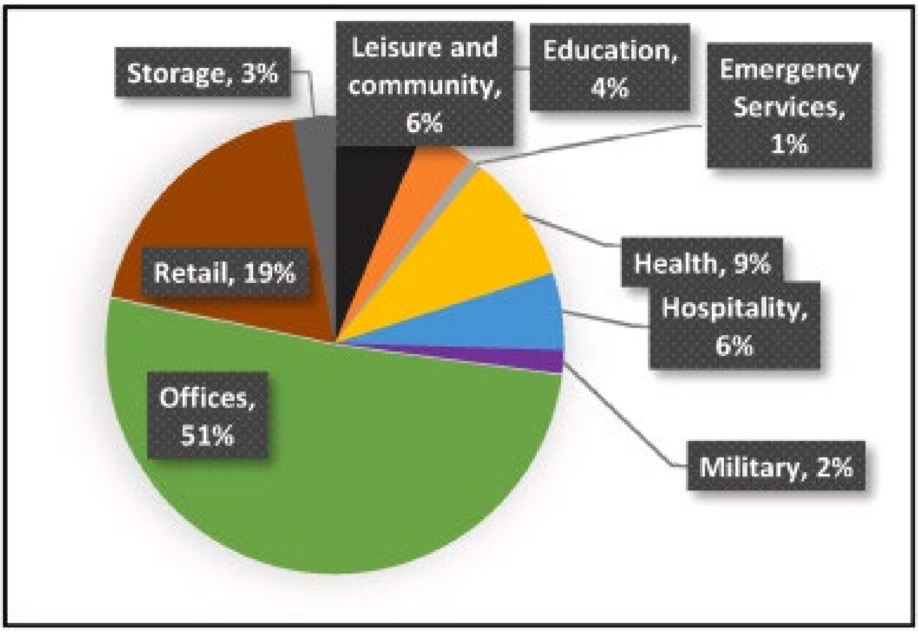
How is the UK demand for electricity for cooling expected to change?

Work done to date on cooling demand in the UK is relatively sparse. Currently, cooling for buildings represents about 3% of total energy demand and 10% of electricity demand in the UK [85].

The vast majority of cooling demand is split between non-domestic buildings (shown in Figure). High levels of active cooling are already deployed in these building types, meaning that there is less room for further growth in this category, with new builds being the exception. Future non-domestic demand will likely to be driven in line with temperature increases, leading to higher power draws on existing systems to meet target comfort levels, rather than an exponential increase due to the installation of new cooling systems.

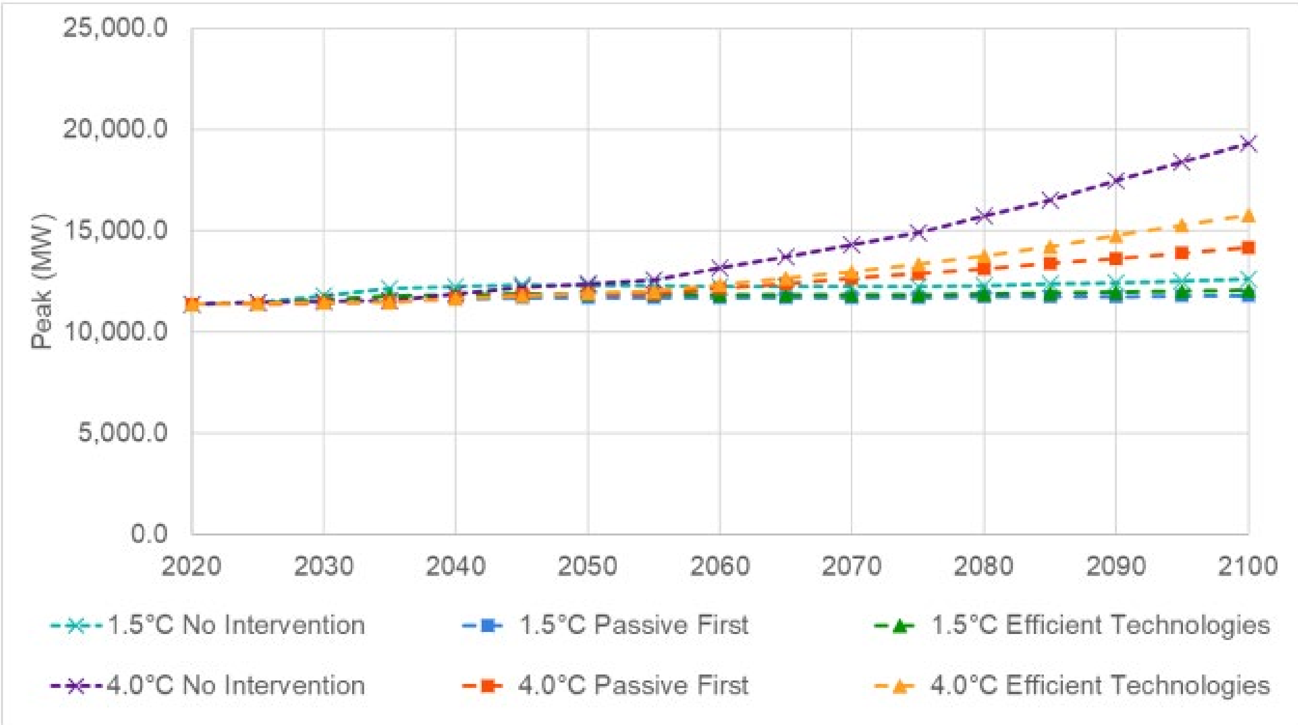
In the UK, as elsewhere, electricity demand for cooling is expected to grow. In general, domestic active cooling measures will present as the single largest growth vector for cooling demand moving forwards, in no small part due to the fact that this sector is currently grossly underrepresented in UK overall cooling demand, leaving a lot of room for growth.

Figure 36 UK energy consumption for cooling of non-domestic building [84]



In 2021 The Department for Business, Energy and Industrial Strategy (BEIS) published a research paper on cooling demands [6]. The paper assessed cooling energy demand and uptake scenarios based upon two climate warming scenarios (+1.5°C and +4°C), and for three different deployment scenarios (No Intervention, Passive First, and Efficient Technologies). Modelled peak demand in each scenario is illustrated in the figure below.

Figure 37 Modelled peak cooling power consumption for the UK [5]



The methodology applied by this study was to calculate and plot cooling measure uptake based upon overall temperature increases, the number and frequency of heatwave events, and the discomfort caused by these events, with the combination of these variables informing the increased uptake of cooling measures across the assessed scenarios. The approach of using thermal discomfort and degree cooling days as a metric for active cooling uptake means this paper does not fully recognise that one of the primary drivers for active and passive cooling measure adoption will be the decarbonisation of UK heating demand through the extensive uptake of heat pumps over the coming decades. To achieve Net-zero by 2050, it will be necessary begin shifting much of UK's heat demand towards electrification. Typically heat pumps for space heating have the capability of operating in reverse, therefore offering both heating and cooling in one system. It seems likely that the proliferation of heat pumps to meet heat decarbonisation goals would be the primary driver for the integration of active cooling into the UK domestic spaces, with active cooling seen as an added benefit or secondary driver. Future work in this space should seek to better understand the scale of cooling demand impacts on the electricity network in line with heat pump adoption pathways.

The method used in the ‘Cooling in the UK’ [86] study mean the results likely predict a deferred uptake of active cooling compared with what may be expected under the heat decarbonisation with heat pumps scenario discussed previously. As such this study likely is not ideal for understanding the timeline of network impacts, but it does offer insight into what future cooling demand could look like following high levels of penetration of active cooling systems within the second half of the century, as well as informing analysis around peak demand.

The Domestic Air Conditioning 2050 project by the UK Energy Research Centre [7] assessed the impact of a number of scenarios of air conditioner adoption on electricity demand. Scenarios ranged from 5-32% of English households adopting air conditioning by 2050. In the highest (i.e. worst case) scenario, UKERC projected that air conditioner adoption would increase the evening peak by 7 GW. The method and resulting data range produced by this study is, as stated by the publisher, “a very simplistic treatment of uptake which uses crude and simple categories”, with uptake compared with the National Grid 2019 FES which showed an uptake of 60% by 2050. The large range of results for cooling system uptake across this and other reviewed papers highlight that there is a large degree of uncertainty.

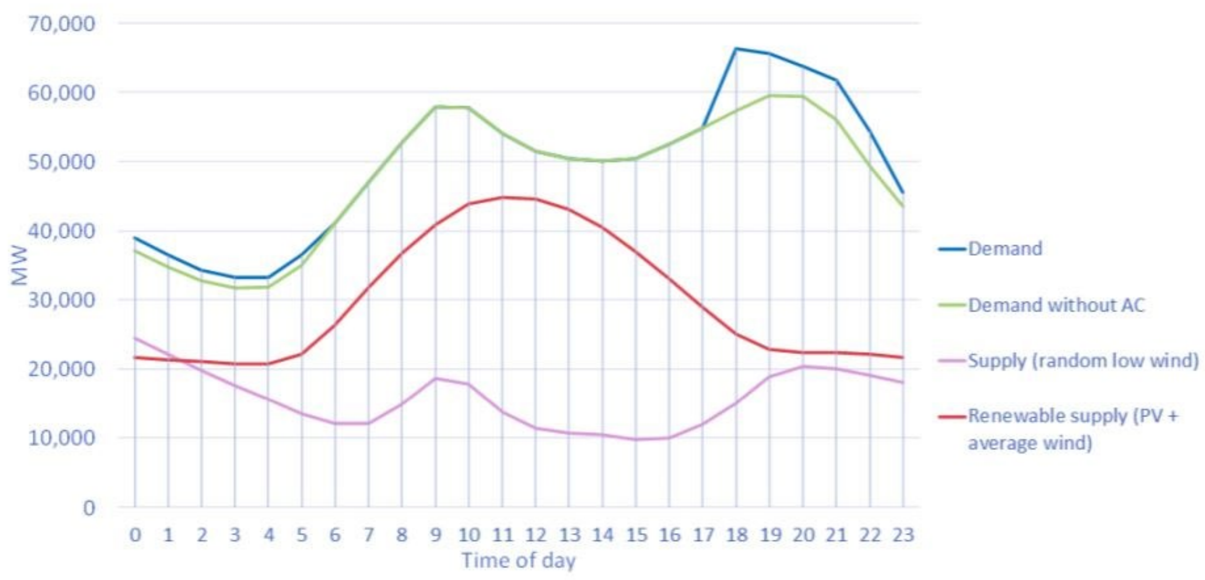
Overall, the literature review has revealed a large amount of uncertainty around the exact trends of future cooling demand and the timing of this demand within the UK, owing in no small part to a lack of data and research into this topic. Many of the papers reviewed highlighted that there are significant data limitations and knowledge gaps regarding this topic in the context of the UK. However, there is a unanimous agreement that as national temperatures rise, and the number of heat wave events increases, significant increases in domestic cooling uptake, and as a result electricity demand, can be expected.

Can the electricity system cope?

Consumption of electricity for cooling is likely to exacerbate the summer peak load. It is likely that the UK electricity system will have adequate capacity built to meet this demand, because the summer peak load is expected to be lower than the winter peak. Currently, space heating and water heating make up a significantly greater proportion of the overall UK energy demand when compared with active cooling, and this would be expected to continue. The UKERC study [7] assumes that heating will largely be electrified in the future, causing the winter evening peak in electricity demand to exceed the summer peak by a factor of two. Assuming that sufficient network capacity is added to electrify heating demands, there should be sufficient capacity to also meet the added electricity demand for cooling in summer months.

There are two caveats to be considered. First, during a heatwave, peak cooling demand is likely to coincide with a reduction in the efficiency across the electricity system, as discussed in previous sections. Indeed, during the 2022 heatwave, electricity demand came very close to outstripping supply, due primarily to reduced output of power plants and efficiency of transmission networks. Second, peak demand for cooling in the summer months is unlikely to coincide with peak solar PV production (see Figure 38). If peak demand coincides with a period of low wind generation, there could be a challenge for the system to meet peak cooling demand (whether winter or summer) with a generation mix dominated by variable renewable electricity.

Figure 38 Summer day – GB electricity demand with and without domestic air conditioning [86]



What adaptation options exist?

The challenge of misalignment between the timing of renewable generation and peaks in electricity demand is not specific to demand spikes caused by heatwaves. Adaptation options to enhance the flexibility of supply are well documented, and include dispatchable generation, storage capacity, and grid interconnections to support the grid during peak times. More research would be needed to investigate the extent to which grid flexibility might be reduced during heatwaves. This should be a subject of interest for DNO networks and more thoroughly considered in their DFES assessments moving forwards.

Other adaptation options focus on promoting energy efficiency and shifting the timing of electricity demand. Demand side management options, including things like V2G/V2H, can shift overall electricity demand to other times of the day, thereby helping to flatten out evening peaks.

Further adaptation options focus specifically on reducing the overall demand for electricity for cooling by adopting more passive measures, as well as increasing the efficiencies of active cooling technologies. For example, as acknowledged in the BEIS paper [86], there are potential synergies between heat decarbonisation and cooling, as passive measures (insulation, ventilation) and active measures (heat pumps) can be used to service both heating and cooling activities and thinking about both simultaneously can introduce increased efficiencies. Th paper found that in the high emissions scenario (4.0°C), the use of efficient technologies might reduce the UK peak cooling power demand by around 3.5GW in 2100 and adopting a passive first approach may reduce it 5.1GW from the projected ~19 GW peak.

Khosravi et al 2023 found that there is a real gap in research and policy surrounding cooling demand, and the interlinks between this and the more thoroughly researched heat decarbonisation pathways should be investigated more to understand possible policy decisions that would support combined decarbonisation, improve efficiency, reduce electricity system stresses, and provide economic support and consumer awareness for optimal solution adoption [6]. Khosravi (2023) also suggests that the use of district heating and cooling schemes should be investigated [6]. These are widely adopted across Scandinavia in particular, and the learnings from these existing study cases should prove useful when considering the best solutions and help identify the potential for combined heating/cooling system decarbonisation approaches. It is important that research is carried out soon, given the relatively early state of the UK's heating/cooling decarbonisation journey, in order to maximise decision making early on and avoid investment and into sub-optimal decarbonisation pathways.

All of the papers reviewed suggest that passive measures should be promoted as the best first step to readying homes for heating and cooling decarbonisation, and that these share many measures such as insulation, double glazed windows, and improved ventilation that would introduce efficiencies for both demand types, and reduce overall electricity demand and peaks from active measures such as heat pumps, air conditioning etc. The UK Heat and Building Strategy (BEIS, 2021) [87] introduced new standards to ensure overheating risks are assessed for all new builds during the design phase, followed up by revisions to the existing Building Regulations in December 2021 that set out passive cooling measures for new builds. It is suggested that more thinking will need to go into the retrofitting of older buildings given that these make up the majority of the UK housing stock.

Appendix 6 – Asset specific adaptation options

A.6.1 Methodology

Evidence extraction

This methodology describes the process undertaken to identify a long-list of potential asset-specific adaptation measures that could be considered to reduce vulnerability and/or exposure, as well as the identification of 'key' or common adaptation measures across all assets and asset categories. The results of the identification of the long list of measures is presented below. The 'key' or common adaptation measures are presented in Section 3 of the report.

References and information relating to potential adaptation measures were identified and extracted through the REA, described in detail in section A.1.1.1. In summary, a total of 2,300 papers underwent title review, out of which 1,250 papers were from google scholar searches and 1,050 were from searches conducted on online publication repositories. 209 papers (out of 2300 that were title screened) passed the title screening stage, and 121 (out of 209 that passed title screening) progressed after the abstract screening, i.e. 121 papers were reviewed in detail for the REA. Of the 121, 30 papers contained references to potential adaptation options.

The information extracted was then reviewed in context of the following questions:

- What are some examples of potential adaptation options i.e. policies, regulations, retrofits etc. that may help to adapt to extreme heat?
- Do these options reduce sensitivity, improve adaptive capacity, or change exposure of the asset to extreme heat?
- Are these options organisational, technical, financial, or ecosystem based?

Potential adaptation options were identified from these selected sources, which were then validated through in-house technical expertise. By leveraging this technical expertise, the identified options were refined and tailored to meet the specific needs of the assets and asset categories, ensuring that the final set of options are practical and feasible.

Cross-analysis

A cross-analysis of the collated measures was conducted to identify common adaptation options across all energy system assets and asset categories. This analysis highlights measures that can be implemented across multiple asset categories to enhance overall system resilience. In the process of conducting cross-analysis to identify key adaptation measures, the initial step involved selecting commonalities from a wide range of adaptation options across all asset categories.

These commonalities were collated into a cohesive set of key options, each grouped by common theme. This thematic grouping was structured to address the diverse needs of different asset categories. For each key option, more detailed information was provided to explain how the measure could be specifically tailored to suit the requirements of each asset category, where necessary.

Subsequently, the remaining adaptation options, which did not fall into the broader thematic categories, were organised into a series of discrete measures. This ensured the less common options could be effectively integrated with due consideration.

This approach was structured to provide both detail and tailoring to the various needs of energy system asset categories.

A.6.2 Results

This section presents potential adaptation measures for specific energy asset categories. These options should undergo detailed analysis to assess their applicability, cost-effectiveness, and feasibility. This initial exercise serves as a preliminary identification of existing adaptation options from existing literature.

The total collation of specific adaptation options is presented in Table 24 Table 25, Table 26, and Table 28, below. These Tables are grouped by asset category. While initial research into a comprehensive breakdown of contextual factors, including co-benefits and potential maladaptation effects has been considered during the analysis, a selection of key associated factors is highlighted here for each adaptation option to maintain the report’s focus and brevity.

Table 24 Electricity generation discrete adaptation options

Adaptation Option	Vulnerable asset
• Upgrading and transitioning the cooling system to a different cooling methodology via the installation of an inlet air cooling system in gas turbine units to maintain its performance during hot ambient air temperatures	Gas Power Plants and CCS
Potential maladaptation: The manufacturing and installation of new cooling systems may generate GHG emissions, due to increased energy use and material consumption	
• Transition from once-through river cooling to open recirculating systems	Nuclear Power Plants
Potential maladaptation: Open recirculating systems require additional water for evaporation during the cooling process. In regions with limited water availability, this could exacerbate water stress, particularly during heatwaves	
• Air-cooled condensers can be sprayed with water to improve cooling: To improve the cooling process, water spraying (or wetting) can be applied to the air passing through the heat exchangers or to the surface of the heat exchanger tubes. By spraying water onto the air or heat exchangers, the process of evaporative cooling is employed	Nuclear Power Plants
Contribution to mitigation: Implementing this will improve cooling efficiency and reduce thermal stress on components like heat exchangers and turbines, leading to lower maintenance requirements and increased equipment lifespan	
• Curtailment strategies to protect equipment	Solar Panels

Adaptation Option	Vulnerable asset
Contribution to mitigation: Allows renewable energy supply to remain operational following extreme heat events	
• Oversizing solar panels can help manage heat dissipation and prolong the lifespan of components	Solar Panels
Potential maladaptation: Oversizing panels may require increased land use and high initial costs for installation	
• Monitoring equipment to reduce damage with SolarEdge Technology with temperature sensors and real-time monitoring ensures system safety in extreme heat by enabling Safe DC, reducing voltage, and turning off generation when needed	Solar Panels
Contribution to mitigation: Allows renewable energy supply to remain operational following extreme heat events	
• Increase dam height to improve water storage capacity	Hydro
Contribution to mitigation: Increasing dam height will increase water storage capacity, allowing for water flow regulation and improved energy generation efficiency during periods of heatwaves. This contributes to mitigation by maximising renewable energy output, and lowering greenhouse gas emissions	
• Adapt turbines and spillways to manage erratic water flow and discharge patterns	Hydro
Enhanced adaptive capacity: By minimising disruption and preventing damage adapting spillways and turbines makes the system less reactive to the stressors of extreme heat	

Table 25 Power networks discrete adaptation options

<table>
<tr><th>Adaptation option</th><th>Vulnerable asset</th></tr>
<tr><td>Building extra capacity and adjusting pole heights to enhance adaptive capacity by reducing risk of thermal overload during heat related demand spikes and by compensating for increased thermal sag during hot weather which help in maintaining safe clearance from ground/structures. Building extra capacity reduces sensitivity by enabling better heat dissipation through larger conductor sizes</td><td>Overhead Lines - Transmission, Distribution, and HVDC lines</td></tr>
<tr><td colspan="2">Enhanced adaptive capacity: By compensating for increased thermal sag and heat dissipation to reduce the risk of thermal overload, these measures strengthen the power network's ability to continue operating under extreme heat and extend the lifespan</td></tr>
<tr><td>Implementing smart grid technology and using larger cables while derating existing ones. Smart grid enable real-time monitoring of cable temperatures and load conditions, allowing for proactive adjustments to prevent overheating.</td><td>Distribution Underground Cables</td></tr>
<tr><td colspan="2">Potential maladaptation: Automation and real-time tracking systems are susceptible to cyberattacks, which could compromise energy assets and grid stability</td></tr>
<tr><td>Larger cables can withstand higher loads and hence provide extra margin before temp thresholds are reached, and enabling better heat dissipation.</td><td>Distribution Underground Cables</td></tr>
<tr><td colspan="2">Potential maladaptation: The installation of new cables may contribute to the generation of GHG emissions due to energy use and material consumption. However, the overall GHG impact depends on the lifecycle analysis. If the upgrades extend the infrastructure's lifespan and reduce failures, the long-term emissions may decrease</td></tr>
</table>

Adaptation option	Vulnerable asset
• Derating involves operating cables below their maximum capacity. This reduces the likelihood of failure during heat waves. By operating at reduced capacities, derated cables experience less thermal degradation"	Distribution Underground Cables
Reduced sensitivity: Derating existing cables contributes to maintaining operational efficiency, and reducing the risk of equipment failure during extreme heat events	
• Separating components into different temperature zones	Power Electronics, Converters, Filters and Interfaces
Reduced sensitivity: Separating components into different temperature zones reduces sensitivity by isolating heat-prone parts and maintaining performance stability	
• Considering transformer-less designs	Power Electronics, Converters, Filters and Interfaces
Reduced sensitivity: Without a transformer, the inverter is smaller and lighter, allowing for better airflow and more effective heat dissipation	
• Optimise inverter design for the envisaged temperature ranges with effective cooling systems	Power Electronics, Converters, Filters and Interfaces
Enhanced adaptive capacity: Cooling systems enhance adaptive capacity by preventing overheating, reducing energy losses, and prolonging equipment lifespan	

<table>
<tr><th>Adaptation option</th><th>Vulnerable asset</th></tr>
<tr><td>Making use of higher-rated batteries for supporting infrastructure of control & monitoring</td><td>Control, monitoring and Metering Equipment</td></tr>
<tr><td colspan="2">Enhanced adaptive capacity: Integrating higher-rated batteries enhances adaptive capacity by improving the resilience of batteries and compensating for battery capacity loss under extreme heat</td></tr>
<tr><td>Incorporate special expansion conductors</td><td>Control, monitoring and Metering Equipment</td></tr>
<tr><td colspan="2">Reduced sensitivity: Incorporating special expansion conductors reduces sensitivity by accommodating temperature-induced expansion and contraction</td></tr>
<tr><td>Install corrosion-resistant materials</td><td>Substation and network earthing systems</td></tr>
<tr><td colspan="2">Reduced sensitivity: High temperatures can accelerate corrosion in substation earthing grids, which can affect the resistivity of the grid and which in turn can impact the effectiveness of earthing systems. Corrosion-resistant materials can preserve their conductive properties better over time, minimising resistance changes caused by environmental extremes</td></tr>
<tr><td>Apply moisture-retaining materials around electrodes</td><td>Substation and network earthing systems</td></tr>
</table>

Adaptation option	Vulnerable asset
Reduced sensitivity: Applying moisture-retaining materials around electrodes reduces sensitivity by maintaining consistent moisture levels and preventing overheating or drying that could impair electrode performance	
• Install earthing systems at greater depths to mitigate temperature effects	Substation and network earthing systems
Reduced exposure: By installing earthing systems at greater depths, exposure to extreme heat and thermal degradation from solar radiation is reduced, as subsurface temperatures are less affected by extreme surface heat	

Table 26 Energy storage discrete adaptation options

Adaptation option	Vulnerable asset
• Adjust charging protocols to avoid high ambient temperatures	Battery Storage Systems
Reduced sensitivity: Adjusting charging protocols to avoid high ambient temperatures reduces sensitivity to extreme heat by preventing overheating and damage to battery storage systems	
• Consider use of alternative battery chemistries which perform better in heat such as LiFePO4	Battery Storage Systems
Reduced sensitivity: Using alternative battery chemistries improves durability and efficiency under extreme heat	

Adaptation option	Vulnerable asset
• Install additional capacity (e.g. plants to charge the thermal stores, to increase flexibility of the system within different ambient *temperatures)*	Thermal Energy Storage
Reduced sensitivity: Installing additional capacity in a thermal energy store reduces sensitivity to extreme heat by enhancing the system's ability to charge and store energy efficiently under varying temperatures	
• Redesign units for thermal expansion	Gas Storage Units
Reduced sensitivity: Redesigning gas units for thermal expansion reduces sensitivity to extreme heat by using materials and structures that accommodate temperature-induced changes, preventing cracking or warping and maintaining pressure stability	

Table 27 Natural gas infrastructure discrete adaptation options

Adaptation option	Vulnerable asset
• More robust pipeline designs - incorporating flexible expansion joints and advanced welding techniques, installing more frequent pressure relief valves and temperature sensors, advanced protective coatings	Gas Transmission and Distribution Network
Enhanced adaptive capacity: More robust pipeline designs enhance adaptive capacity by reducing the risk of failure and minimising the risk of damage under extreme heat	
• Investigate the techno-economic feasibility of substituting carbon steel pipes with glass reinforcement epoxy (GRE) systems	Gas Transmission and Distribution Network

Adaptation option	Vulnerable asset
Reduced sensitivity: Replacing carbon steel pipes with GRE could result in performance benefits in the face of extreme heat due to superior corrosion and heat resistance	
• Ensure timely decommissioning of valves & regulators that are nearing end of useful life/performance is no longer satisfactory	Compressor Valves and Regulators
Reduced sensitivity: Timely decommissioning helps reduce sensitivity by minimising failure points in the infrastructure, aged components are more prone to failure in extreme heat and degrade more rapidly at high temperatures	
• Adapt to the impact of raised temperatures on turbine compressors by using intake cooling	Compressor Valves and Regulators
Enhanced adaptive capacity: Cooling intake air/gas enhances adaptive capacity by maintaining the air or gas density in extreme heat that helps in maintaining compression efficiency, and reducing the rate of material degradation	

Table 28 Hydrogen discrete adaptation options

Adaptation option	Vulnerable asset
• Continuous practice of temperature and quality control on effluent water	Hydrogen Electrolysers
Enhanced adaptive capacity: Controlling effluent water helps to protect components, maintain efficiency and prolong the system's lifespan under extreme heat conditions, enhancing adaptive capacity	
• Ensure an oversupply of coolant to eliminate additional risks	Hydrogen Electrolysers

Adaptation option	Vulnerable asset
Potential maladaptation: Increased risk of leaks, and increased generation of associated waste products	
• Introduce additional buffers for safety zones to ensure that any potential risks associated with extreme heat can be circumvented. This can include more frequent monitoring and maintenance, as well as increased requirement for PPE	Hydrogen Electrolysers
Enhanced adaptive capacity: By protecting equipment and personnel and ensuring safe operations in the face of extreme heat, this contributes to enhanced adaptive capacity	
• Ensure minimal flammable flora exist in close proximity to the plant that could increase the risks of runaway fires; if plant locations exist nearby susceptible flora, active tracking of fire events to properly plan for emergencies	Hydrogen Electrolysers
Enhanced adaptive capacity: Ensuring minimal flammable flora exist in close proximity to the plant contributes by ensuring safe operations in the face of extreme heat and heat waves, this contributes to enhanced adaptive capacity	
• Stringent maintenance of the systems following heatwaves to ensure no significant degradation of equipment has occurred; implement routine stress analysis on above-ground installations to ensure they can withstand operational pressures and mitigate stress levels effectively	Hydrogen Electrolysers
Enhanced adaptive capacity: Stringent maintenance and stress testing reduces sensitivity to extreme heat by identifying and addressing heat-induced degradation	

Adaptation option	Vulnerable asset
• Assess the impact of heatwaves on water supply to maintain the operational efficiency of electrolyser plants and plan for alternative emergency water supply options. Should a heatwave significantly impact the imminent supply of water to the electrolyser, alternative emergency water supply options should be planned or the system would need to be temporarily shut down	Hydrogen Electrolysers
Enhanced adaptive capacity: Reducing vulnerability to water scarcity resulting from extreme heat enhances adaptive capacity by increasing the reliability of hydrogen electrolysers under extreme-heat induced water stress	
• Technologies like advanced liquid cooling systems, phase-change materials, or thermoelectric coolers	Hydrogen Electrolysers
Reduced sensitivity: Technologies like advanced liquid cooling systems reduce sensitivity in hydrogen electrolyser assets by preventing overheating, maintaining operational efficiency, and reducing the risk of equipment failure during extreme heat events	
• Thermal energy storage systems can absorb excess heat during peak heatwave periods and dissipate it when temperatures drop, reducing the cooling system's strain	Hydrogen Electrolysers
Reduced sensitivity: Using thermal energy storage systems leads to reduced sensitivity by allowing protective measures to be taken to reduce potential damage to equipment	
• Seals and joints should be replaced at regular intervals based on operating temperature history, not just the number of cycles or hours of use	Hydrogen Pipelines

Adaptation option	Vulnerable asset
Reduced sensitivity: Replacing seals and joints based on operating temperature history helps reduce sensitivity by minimising failure points in infrastructure, as aged components are more prone to failure in extreme heat and degrade more rapidly at high temperatures	
• Consider using heat resistant alternative technologies including Perfluoro elastomers (FFKM/Kalrez) in place of elastomers	Hydrogen Pipelines
Reduced sensitivity: Upgrading to heat-resistant materials improves durability and efficiency under extreme heat, by reducing thermal expansion and preventing component degradation	

References

[1] Press Office, “A milestone in UK climate history,” MET Office.

[2] BBC NEWS, “UK heatwave: Thousands suffer power cuts after equipment overheats,” BBC NEWS.

[3] P. R. G. P. T. G. and D. M. J. Dr Iain Staffell, “How heat waves will change the power system,” Electric Insights - Imperial College London .

[4] BBC NEWS, “UK heatwave: Thousands suffer power cuts after equipment overheats.”

[5] F. Khosravi, R. Lowes, and C. E. Ugalde-Loo, “Cooling is hotting up in the UK,” *Energy Policy*, vol. 174, p. 113456, Mar. 2023, doi: 10.1016/j.enpol.2023.113456.

[6] F. Khosravi, R. Lowes, and C. E. Ugalde-Loo, “Cooling is hotting up in the UK,” *Energy Policy*, vol. 174, 2023, doi: 10.1016/j.enpol.2023.113456.

[7] J. Crawley, X. Wang, S. Ogunrin, I. Vorushlyo, and S. Taneja, “IVUGER Report Domestic Air Conditioning in 2050.”

[8] E. & I. S. Department for Business, “Updated energy and emissions projections 2021 to 2040 ,” Oct. 2022.

[9] M. Dumas, B. Kc, and C. I. Cunliff, “Extreme weather and climate vulnerabilities of the electric grid: A summary of environmental sensitivity quantification methods,” Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2019.

[10] F. Urban and T. Mitchell, “Climate change, disasters and electricity generation,” *Strengthening climate resilience discussion paper*, vol. 8, pp. 22–23, 2011.

[11] R. Schaeffer *et al.*, “Energy sector vulnerability to climate change: A review,” *Energy*, vol. 38, no. 1, pp. 1–12, 2012.

[12] M. Panteli and P. Mancarella, “Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies,” *Electric Power Systems Research*, vol. 127, pp. 259–270, 2015.

[13] J. Sathaye *et al.*, “Estimating risk to California energy infrastructure from projected climate change,” 2012.

[14] S. N. Chandramowli and F. A. Felder, “Impact of climate change on electricity systems and markets–A review of models and forecasts,” *Sustainable Energy Technologies and Assessments*, vol. 5, pp. 62–74, 2014.

[15] M. T. Craig *et al.*, "A review of the potential impacts of climate change on bulk power system planning and operations in the United States," *Renewable and Sustainable Energy Reviews*, vol. 98, pp. 255–267, 2018.

[16] P. Dowling, "The impact of climate change on the European energy system," *Energy Policy*, vol. 60, pp. 406–417, 2013.

[17] H. Zhang, Y. Da, X. Zhang, and J.-L. Fan, "The impacts of climate change on coal-fired power plants: evidence from China," *Energy Environ Sci*, vol. 14, no. 9, pp. 4890–4902, 2021.

[18] N. Norouzi, "The Pahlev Reliability Index: A measurement for the resilience of power generation technologies versus climate change," *Nuclear Engineering and Technology*, vol. 53, no. 5, pp. 1658–1663, 2021.

[19] Jacques. Després and Marko. Adamovic, *Seasonal impacts of climate change on electricity production : JRC PESETA IV project : Task 4*. Publications Office of the European Union, 2020.

[20] J. A. Añel, M. Fernández-González, X. Labandeira, X. López-Otero, and L. De la Torre, "Impact of cold waves and heat waves on the energy production sector," *Atmosphere (Basel)*, vol. 8, no. 11, p. 209, 2017.

[21] P. Campbell. Johnston, J. Frazier. Gomez, and B. Laplante, *Climate risk and adaptation in the electric power sector*. Asian Development Bank, 2012.

[22] M. D. Bartos and M. V Chester, "Impacts of climate change on electric power supply in the Western United States," *Nat Clim Chang*, vol. 5, no. 8, pp. 748–752, 2015.

[23] C. Zamuda *et al.*, "US energy sector vulnerabilities to climate change and extreme weather," *US Department of Energy, https://energy. gov/sites/prod/files/2013/07/f2/20130716-Energy% 20Sector% 20Vulnerabilities% 20Report. pdf*, 2013.

[24] M. R. Allen-Dumas Binita KC Colin I Cunliff, "Extreme Weather and Climate Vulnerabilities of the Electric Grid: A Summary of Environmental Sensitivity Quantification Methods," 2019. [Online]. Available: http://www.osti.gov/scitech/

[25] L. V Nefedova and D. A. Solovyev, "Assessment of the global climate change impact on Fuel and Energy Complex infrastructure and adaptation opportunities in the Russian Arctic," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2020, p. 012040.

[26] A. Patt, S. Pfenninger, and J. Lilliestam, "Vulnerability of solar energy infrastructure and output to climate change," *Clim Change*, vol. 121, pp. 93–102, 2013.

[27]. "2 Wind."

[28] I. Tobin *et al.*, "Vulnerabilities and resilience of European power generation to 1.5 C, 2 C and 3 C warming," *Environmental Research Letters*, vol. 13, no. 4, p. 044024, 2018.

[29] B. Tarroja, K. Forrest, F. Chiang, A. AghaKouchak, and S. Samuelsen, "Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California," *Appl Energy*, vol. 237, pp. 353–366, 2019.

[30] J. Cronin, G. Anandarajah, and O. Dessens, "Climate change impacts on the energy system: a review of trends and gaps," *Clim Change*, vol. 151, no. 2, pp. 79–93, 2018.

[31] T. K. Mideksa and S. Kallbekken, "The impact of climate change on the electricity market: A review," *Energy Policy*, vol. 38, no. 7, pp. 3579–3585, 2010.

[32] D. E. H. J. Gernaat, H. S. de Boer, V. Daioglou, S. G. Yalew, C. Müller, and D. P. van Vuuren, "Climate change impacts on renewable energy supply," *Nat Clim Chang*, vol. 11, no. 2, pp. 119–125, 2021.

[33] D. Falabretti, L. Lo Schiavo, S. Liotta, and A. Palazzoli, "A novel method for evaluating the resilience of distribution networks during heat waves," *International Journal of Electrical and Electronic Engineering and Telecommunications*, vol. 9, no. 2, pp. 73–79, 2020.

[34] N. M. Zainuddin *et al.*, "Review of thermal stress and condition monitoring technologies for overhead transmission lines: Issues and challenges," *IEEE Access*, vol. 8, pp. 120053–120081, 2020.

[35] R. Entriken and R. Lordan, "Impacts of extreme events on transmission and distribution systems," in *2012 IEEE Power and Energy Society General Meeting*, IEEE, 2012, pp. 1–10.

[36] D. Burillo, M. Chester, and B. Ruddell, "Electric grid vulnerabilities to rising air temperatures in Arizona," *Procedia Eng*, vol. 145, pp. 1346–1353, 2016.

[37] M. Halat, X. Clotet, V. Gaitán, and D. Bechrakis, "Protection elements and methods in Energy and Telecom infrastructure," 2015.

[38] T. Huang *et al.*, "Analysis and visualization of natural threats against the security of electricity transmission system," *The Scientific Bulletin of Electrical Engineering Faculty*, 2017.

[39] O. Kondrateva, E. Myasnikova, and O. Loktionov, "Analysis of the climatic factors influence on the overhead transmission lines reliability," *Rigas Tehniskas Universitates Zinatniskie Raksti*, vol. 24, no. 3, pp. 201–214, 2020.

[40] P. S. Paul *et al.*, "Effect of Natural and Man-made Disasters on Distribution System".

[41] S. D. M. Salas and A. Michiorri, "The Climate Change Impact on Power Grid Transmission Capacity," 2024.

[42] E. Oliver, D. Martin, O. Krause, S. Bartlett, and C. Froome, "How is climate change likely to affect queensland electricity infrastructure into the future?," in *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, IEEE, 2015, pp. 1–6.

[43] X. Hu, *Impacts of Climate Change on Power Systems*. The University of Manchester (United Kingdom), 2016.

[44] S. Blake, P. Davison, D. Greenwood, and N. Wade, "Climate change risks in electricity networks," *Infrastructure Asset Management*, vol. 2, no. 2, pp. 42–51, 2015.

[45] L. A. Bollinger and G. P. J. Dijkema, "Evaluating infrastructure resilience to extreme weather–the case of the Dutch electricity transmission network," *European Journal of Transport and Infrastructure Research*, vol. 16, no. 1, 2016.

[46] N. Abi-Samra, *Power Grid Resiliency for Adverse Conditions*. Artech House, 2017.

[47] S. Majithia, "Improving resilience challenges and linkages of the energy industry in changing climate," *Weather Matters for Energy*, pp. 113–131, 2014.

[48] E. Hossain, S. Roy, N. Mohammad, N. Nawar, and D. R. Dipta, "Metrics and enhancement strategies for grid resilience and reliability during natural disasters," *Appl Energy*, vol. 290, p. 116709, 2021.

[49] A. M. Brockway and L. N. Dunn, "Weathering adaptation: Grid infrastructure planning in a changing climate," *Clim Risk Manag*, vol. 30, p. 100256, 2020.

[50] S. Aivalioti, "Electricity sector adaptation to heat waves," *Columbia Law School, Sabin Center for Climate Change Law White Paper*, 2015.

[51] R. Zimmerman and C. Faris, "Infrastructure impacts and adaptation challenges.," *Ann N Y Acad Sci*, vol. 1196, no. 1, 2010.

[52] "Adaptation to Climate Change Task Group Gas & Electricity Transmission and Distribution Network Companies 3 rd Round Climate Change Adaptation Report," 2021.

[53] P. Campbell. Johnston, J. Frazier. Gomez, and B. Laplante, *Climate risk and adaptation in the electric power sector*. Asian Development Bank, 2012.

[54] "Impacts of climate change on defence-related critical energy infrastructure EUR 31270 EN", doi: 10.2760/116974.

[55] "RECENT HEAT EXTREMES IN CONTEXT."

[56] "Adapting to Climate Change," 2021.

[57] L. Calcara, A. Di Pietro, S. Giovinazzi, M. Pollino, and M. Pompili, "Towards the resilience assessment of electric distribution system to earthquakes and adverse meteorological conditions," in *2018 AEIT International Annual Conference*, IEEE, 2018, pp. 1–6.

[58] C. Edison, "Climate Change Vulnerability Study," *published December*, 2019.

[59] E. Amicarelli, L. Ferri, M. De Masi, A. Suich, and G. Valtorta, “Assessment of the resilience of the electrical distribution grid: E-distribuzione approach,” in *2018 AEIT International Annual Conference*, IEEE, 2018, pp. 1–6.

[60] J. A. Sathaye *et al.*, “Estimating impacts of warming temperatures on California’s electricity system,” *Global Environmental Change*, vol. 23, no. 2, pp. 499–511, 2013.

[61] “Third Round Climate Change Adaptation Report National Grid Gas plc,” 2021.

[62] N. A. Ibrahim, S. R. Wan Alwi, Z. Abd Manan, A. A. Mustaffa, and K. Kidam, “Climate change impact on solar system in Malaysia: Techno-economic analysis,” *Renewable and Sustainable Energy Reviews*, vol. 189, Jan. 2024, doi: 10.1016/j.rser.2023.113901.

[63] A. Altamimi and D. Jayaweera, “Reliability of power systems with climate change impacts on hierarchical levels of PV systems,” *Electric Power Systems Research*, vol. 190, Jan. 2021, doi: 10.1016/j.epsr.2020.106830.

[64] “User Manual SG125HV-30 PV Grid-connected Inverter.” [Online]. Available: www.sungrowpower.com.

[65] F. Leng, C. M. Tan, and M. Pecht, “Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature,” *Sci Rep*, vol. 5, Aug. 2015, doi: 10.1038/srep12967.

[66] S. Ma *et al.*, “Temperature effect and thermal impact in lithium-ion batteries: A review,” Dec. 01, 2018, *Elsevier B.V.* doi: 10.1016/j.pnsc.2018.11.002.

[67] A. Pesaran, S. Santhanagopalan, and G.-H. Kim, “Addressing the Impact of Temperature Extremes on Large Format Li-Ion Batteries for Vehicle Applications (Presentation), NREL (National Renewable Energy Laboratory),” 2013.

[68] S. Wang *et al.*, “Effects of Current and Ambient Temperature on Thermal Response of Lithium Ion Battery,” *Batteries*, vol. 8, no. 11, Nov. 2022, doi: 10.3390/batteries8110203.

[69] “NGN-CCA-Rnd-3-Report-FINAL-DECEMBER-2021”.

[70] SGN, “3 rd Round Climate Change Adaptation Report,” 2021.

[71] “Adaptation to Climate Change Task Group Gas & Electricity Transmission and Distribution Network Companies 3 rd Round Climate Change Adaptation Report,” 2021.

[72] J. Bruzgul *et al.*, “Potential Climate Change Impacts and Adaptation Actions for Gas Assets in the San Diego Gas and Electric Company Service Area,” 2018.

[73] J. Udie, S. Bhattacharyya, and L. Ozawa-Meida, “Vulnerability assessment of climate change impact on critical oil/gas infrastructure: a decision-maker’s perception in the Niger Delta,” *The International Journal of Climate Change: Impacts and Responses*, vol. 10, no. 4, pp. 25–39, 2018.

[74] "Briefing report for Henderson Global Investors, Insight Investment, Railpen Investments and Universities Superannuation Scheme Oil and gas Understanding the investment implications of adapting to climate change," 2009. [Online]. Available: www.acclimatise.uk.com/resources/investors

[75] Stargate Hydrogen, "Stargate Hydrogen gateway series technical specification," 2022, *Stargate Hydrogen*.

[76] Sagim Hydrogen henerators, "TECHNICAL SPECIFICATIONS FOR AN ELECTROLYTIC HYDROGEN GENERATOR TYPE M 5000," *Sagim Hydrogen henerators*.

[77] Enapter, "AEM Electrolyser EL 4.0," 2023, *Enapter Company*.

[78] K. Fatima, H. Shareef, F. B. Costa, A. A. Bajwa, and L. A. Wong, "Machine learning for power outage prediction during hurricanes: An extensive review," *Eng Appl Artif Intell*, vol. 133, p. 108056, Jul. 2024, doi: 10.1016/J.ENGAPPAI.2024.108056.

[79] E. Tsioumpri, B. Stephen, and S. D. J. McArthur, "Weather related fault prediction in minimally monitored distribution networks," *Energies (Basel)*, vol. 14, no. 8, Apr. 2021, doi: 10.3390/en14082053.

[80] A. Mazza, G. Chicco, and C. L. T. Borges, "Investigation on the Impact of Heat Waves on Distribution System Failures."

[81] A. Kenward and U. Raja, "BLACKOUT: EXTREME WEATHER, CLIMATE CHANGE AND POWER OUTAGES," 2014. [Online]. Available: www.climatecentral.org

[82] S. Dunn, S. Wilkinson, D. Alderson, H. Fowler, and C. Galasso, "Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database," *Nat Hazards Rev*, vol. 19, no. 1, Feb. 2018, doi: 10.1061/(asce)nh.1527-6996.0000267.

[83] *2014 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS) : conference proceedings : July 7-10, 2014, Durham, UK*. IEEE, 2014.

[84] V. Rizeakos, A. Bachoumis, N. Andriopoulos, M. Birbas, and A. Birbas, "Deep learning-based application for fault location identification and type classification in active distribution grids," *Appl Energy*, vol. 338, p. 120932, May 2023, doi: 10.1016/J.APENERGY.2023.120932.

[85] F. Khosravi, R. Lowes, and C. E. Ugalde-Loo, "Cooling is hotting up in the UK," *Energy Policy*, vol. 174, p. 113456, Mar. 2023, doi: 10.1016/J.ENPOL.2023.113456.

[86] "Cooling in the UK," 2021.

[87] D. for Business and I. Strategy, "HM Government – Heat and Buildings Strategy."

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